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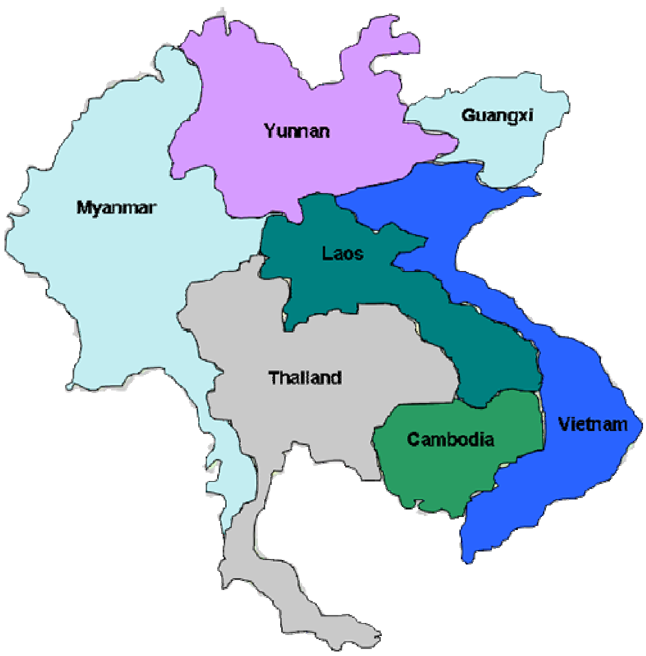

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Sustainable Management of Hydropower in Lao PDR

Seumkham Thoummavongsa and Xayphone Bounsou

Abstract— *Laos has potential for new hydropower plants with total installed capacity of 28,000 MW. Today, Laos has hydropower plants with a capacity of 3,200 MW. Hydropower projects involve a number of multiple stakeholders with various interests. Effective management and environment considerations are important to ensure sustainable development within the sector. Even though substantial improvements in policy procedures, legal requirements and assessment guidelines have been made there is still room for improvements. A major problem is related to benefit sharing, capacity building and institutional aspects. Development of hydropower needs to be sustainable, with minimal adverse social and environmental impacts. Hydropower should, as renewable source, also be a viable and profitable energy solution contributing to a positive economic development. Hydropower development should respond to realities of the country and to the energy market. Hydropower must be developed in the context of broader goals, including environmental management, poverty alleviation institutional and social development along with integrated water and energy management. Sustainable development of hydropower requires the integration of economic and social development as well as environmental protection. In planning of hydropower projects the following parameters are important: efficiency, participatory decision-making, sustainability, and accountability along with precautionary approach to ensue an environmentally sound development.*

Keywords— **Hydropower, sustainable, planning, development, management and benefit sharing.**

1. INTRODUCTION

The economic development in the Lao People's Democratic Republic (Lao PDR) has been firmly rooted in developing its abundant natural resources, including water, minerals, forests, wetlands and biodiversity. Although a relatively small percentage of 2.8 of the national water resources are developed for storage or abstraction, water is the fundamental resource for hydropower generation which has been identified as the major national development opportunity [1].

The Lao PDR has the potential to build more than 70 hydropower plants (Dams) with a total installed capacity of about 28,000 MW. So far, the Lao PDR has built only 14 hydropower plants or power dams with an installed capacity of 3,200 MW (year 2012) [2]

There is a need to develop new, more sustainable environmental planning and policy approaches that integrate social and ecological concerns in hydropower projects in the country. These social ecological approaches should go hand in hand with present long term rehabilitation efforts carried out by the rural societies to restore damaged aquatic environments from previous hydropower projects. Hydropower is not just a means of combating GHG emissions; water storage also supports adaptation to climate changes. Water and energy are essential to the alleviation of poverty. Climate changes make this more urgent and for many countries the development of hydropower can be a vital and important part of the answer. Due to the increased demands of reliable supplies of electric power, irrigation, and drinking water the number of new small and medium sized hydropower reservoirs is increasing dramatically in the world.

In the Lao National Energy Policy it is important to maintain and expand affordable, reliable and sustainable electricity production and supply in order to support a positive economic and social development in the country. Also improvements and expansion of transmission networks to support the rapidly growing industrialization and modernization process and the intergradations of the power sector in the ASEAN community through its power exchange programs will require extra power capacity. To use or tap the country's large hydropower potentials will however require participation of private developers;

Hydropower energy is a key element of sustainable energy production. Hydropower energy contributes holistically to our combined goals of having economic growth, a positive social development, increased energy security, and a good environmental protection. All factors promising a brighter, safer, and cleaner future for the Lao people and for the coming generations. Some initial progress has already been made. Putting renewable energy solutions into practice on a national scale, in a world that has organized its institutional, industrial, financial, and governmental systems principally around the supply and use of fossil fuels is a very challenging task [3].

On a regional scale, power supply is the most capital

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intensive sector of all. The industrial and commercial sector and every aspect of social progress are heavily dependent on reliable energy supply. At the same time there are significant scopes for the development of hydropower on the existing power production structure and the modernization of the existing hydropower plants to improve efficiency and development of hydropower plants to provide energy to rural, remote and under-supplied regions. The development, renovation, and rehabilitation of these existing hydro power plants will together with new hydropower projects, lead to a situation where significant additional clean and renewable energy capacity can be achieved.

The purpose of this paper is to analyze socio-economic and environmental sustainability considerations to be developed in the Lao PDR. The paper discusses the existing environment aspects associated with hydropower planning, development, and other challenges related to that sector in the Lao PDR. The paper aims to highlight the problems and constraints in the hydropower sector and suggest some opportunities to meet the emerging challenges, the implementation of policies and institutional strengthening processes that will lead to an improved and sustainable development of the hydropower sector in the country. Furthermore, the paper can be considered a discussion paper which can help and give some guidance of how to integrate sustainable development and management considerations into hydropower planning, development and management. It also provides policy makers related to Theun Hinboun Hydropower Expansion with the kind of information they need in order to achieve a better understanding of the environmental, social and economical implications of hydropower developments and management.

2. HYDROPOWER DEVELOPMENT AND MANAGEMENT CONTEXT

The Lao PDR is in the midst of relatively rapid economic growth and natural resource development. Hydropower, mining and agriculture are major sectors. Urban areas are also growing as the population reallocate as a result of the commercial and industrial development in the major towns in Lao. As a result, there are increasing pressures on the environment and an increasing need to manage natural resources in a sustainable manner. The Hydropower generation has been expanded from 33 MW in 1975 (independent power production) to 1,937 MW in 2010. 99.8% of the power production is based on hydropower, 0.07% (1.51MW) from diesel generators and 0.02% (0.47MW) from Solar Power installations [7]. Currently, the electrification ratio in the country is approximately 80% or 1,060,413 households in 2012 and is expected to increase to 90% in 2020.

Hydropower has been perceived and promoted as a comparatively clean, low cost renewable source of energy that relies on proven technology [11]. Except for the reservoir development, which gives the hydropower a big water footprint, [4] it is a non-consumptive use of water. At the same time, the hydropower can also be viewed as a large ‘ecological footprint’ as it has substantial impacts on the natural environment because of its use and reliance upon the existing natural resources [5].Further, classified as a clean, renewable energy resource, hydropower can reduce the net production of greenhouse gasses by moving economies to a lower-carbon future by replacing other forms of power generation [6].

There are risks inherent with the development and operation of hydropower. These risks cover a range of financial, engineering, hydrologic, geological, and market concerns with particular attention to environmental protection, social aspects, resettlement and relocation of people. Hydropower reservoirs have a large number of potential cross-sectional impacts including changes of downstream flows and water quality, dam safety, reservoir fishing, resettlement, ecological impacts, and flood control [10, 11]. As a consequence of a wide variety of impacts and risks, the definition of acceptable hydropower development has changed into a situation where it is needed to ensure the core principles and parameters of sustainable development [8, 9].

2.1 Sustainable Development

The Brundtland Commission's report defined sustainable development as "a development which meets the needs of current generations without compromising the ability of future generations to meet their own needs". The concept supports strong economic and social development, in particular for the low income people. At the same time it underlines the importance of protecting the natural resource base and the environment. Economic and social well-being cannot be improved with measures that destroy the environment. Intergenerational solidarity is also crucial: any development has to take into account its impact on the opportunities for future generations [12].

Sustainable development requires the integration of three components – economic development, social development and environmental protection – as independent, mutually reinforcing pillars. Eradicating poverty, changing unsustainable patterns of production and consumption, and protecting and managing the natural resource base stressing the economic and social development are overarching objectives of, and essential requirements for sustainable development [12].

International organizations like the International Hydropower Association (IHA) [13] and the World Commission on Power Dams are among the international financiers [14] who have produced guidelines for how to promote greater consideration of environmental, social and economic aspects in the sustainability assessment of hydropower projects. This also accounts for the guidelines for the management and operation of existing hydropower schemes.

While there are disagreements on some aspects relating to WCD’s detailed recommendations, there is a clear acceptance of the core values listed in the report, which are equity, efficiency, participatory decision-making, sustainability, and accountability [13].

Also the values of precautionary approach and eco-efficiency to environmental management have been used in developing sustainable hydropower. The precautionary principle and the principle that preventive action should be taken can guide the decision makers in the hydropower sector and eliminate some of the risks and uncertainties in the sector. [15].

Some of the precautionary principles are made in the Rio Declaration on Environment and Development, 1992, where it is stated that: Where there are threats of serious or irreversible environmental damage, the lack of full scientific certainty shall not be used as a reason for postponing cost effective measures to prevent environmental damages. This statement may be extended to include any risk, such as economic, ecological or social risks [16]. IHA [13] believes that the evaluation of the hydropower generation options should be based upon life-cycle analysis of alternative technologies,, the scientific and technical uncertainties taken into account.

Eco-efficiency is based upon the idea that doing more with less – is the core of the business case for sustainable development. Combining environmental and economic operational excellence to deliver goods and services with lower external impacts and higher quality-of-life benefits is a key factor in pursuing sustainable development strategy for the hydropower business [17].

At the domestic level, good governance with sound environmental, social and economic policy, together with democratic institutions responsible to fulfil the needs of people, following the prevailing laws and taking the necessary anticorruption measures are carried out on the basis of sustainable development [17]. Sustainability is based on due considerations given to interrelationships and integration of competing needs. Therefore, it is of prime importance that the national and/or regional policy context takes into account all cross-sectional issues, for example through Integrated Water Resources management (IWRM) [17].

Hydropower development must adopt the dual perspective of integrated water resources management and sustainable energy development. [14]. Integrated water resources management is about strengthening frameworks for water governance to foster a good decision-making in response to changing needs. Here, the rather universal definition of IWRM "as a process that promotes the coordinated development and management of water, land and related resources in order to maximize the economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" is important [18]. Such decision support systems as IWRM are particularly appropriate and useful in hydropower development during the implementation process with a participatory, transparent multi-stakeholder approach [16].

Certain forms of benefit sharing (national-to local) should be used in order to achieve poverty reduction targets. This is important when poverty levels in hydropower project areas often are much higher than the provincial or national averages. This benefit sharing approach should be done for a period of time until poverty levels are reduced to acceptable levels. Only then it is possible to focus on other socio-economic issues that the authorities consider important [36].

The following figure shows the evolution in the view and treatment of power dam affected communities

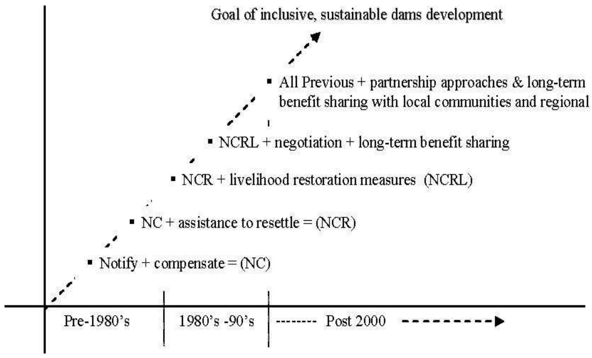

Fig. 1. Era of Typical Practice

The above figure illustrates the development in the hydro power sector the last three decades.

The Lao National Sustainable Hydropower Policy (NHSP) is founded on three important principles: (a) *economic sustainability* relies upon the maintenance of the renewable resource base, and the use of non-renewable resources to support the development of other factors of production; (b) *social sustainability* is based upon the principles of public involvement and participation, including, mutual understanding and consensus; (c) *ecological sustainability*, which relies upon the avoidance if irreversible environmental impacts such as the loss of biodiversity loss, accumulation of persistent pollutants, or disruption of ecological cycles [19].

3. METHODOLOGY

The paper is based on an empirical analysis of primary and secondary data and information; official government documents and relevant literature, a series of workshops of the Future Resource and Economy Policies in Lao PDR until 2020 as well as interviews with government officials and power sector and environmental experts.

4. SUSTAINABLE MANAGEMENT OF HYDROPOWER IN LAO PDR

4.1 Social and Environmental Sustainability

Hydropower development in Lao PDR needs to be sustainable with minimal adverse social and environmental impacts, while remaining a viable and profitable energy solution supporting the economic development in the country. When planning new hydropower projects, site selection, design, construction and operation of hydropower projects there is a need to consider the environmental and social impacts in a manner suitable to the environment and to the society. The Government is currently committed to reduce the existing dependence on fuel wood and imported fossil fuels by promoting to the extent possible to use renewable resources for production of electrical energy [20]. The rural Lao remains an essentially agrarian society, and the livelihoods of its people are strengthened by the presence of healthy and diversified ecosystems that provide them with living sustenance and additional income. Therefore the issue of sustainability is an important one [21].

The Lao Government has developed and improved the domestic legislation related to the hydro power sector; the Law on Water and Water Resources (1996), Forestry Law (2007 updated), Land Law (1997, amended in 2003), Agriculture Law (1998), and Environmental Protection Law (1999) to deal with sustainability and environmental conservation issues. The present legislation together with various regulations ensures sustainable development within the hydropower sector.

According to the Environmental Protection Law (1999), and Decree on Environment and Social Impact Assessment No. 112 (2010), the hydropower projects with an installed capacity of more than 15 MW must produce an Environment and Social Impact Assessment (ESIA) Report and an Environmental Management Plan (EMP) [22]. The Electricity Law (2011) furthermore stipulates that investors in electricity production have an obligation to protect the environment; take the necessary social, environmental considerations. The assessment consists of the following main contents or sections: 1. Assessment of environmental impact in each case, together with proposals of methods and measures for solving or mitigating any adverse impacts on the environment, water resources, land surface or underground, ecology, biodiversity and aquatic and wildlife animals habitats; 2. an estimate of the damage and resettlement issues of people affected by the electricity project; 3. Means to mitigate the impacts of water volume, including the accumulated impacts of the downstream reservoir of the dam; 4. Cover the expenses for restoration of the impacts mentioned in section 1, 2 and 3 of this Article. These extra costs shall be incorporated into the total project cost [23]. Moreover, the recently enacted Lao Technical Electric Standards provides all the necessary guidelines to maximize power dam safety during construction, operation and management. The Lao ESIA process is largely compatible with international standards and guidelines for conducting ESIAs, and the bottom line is that construction activities cannot start before an approval from the Ministry of Natural Resources and Environment has been granted. [10]. The social and environmental safeguards used by the International Development Banks have enhanced the implementation processes of many hydropower developmental projects in Lao PDR, which in general lacks the necessary human and technical skills, and financial resources.

Concerning the Nam Theun 2 Hydropower Project, a lot of lessons has been learnt from previous experiences. Now, issues like environmental impact and resettlement have been addressed and have resulted in revised project preparation and implementation [25]. The aim of the National Policy on Environmental and Social Sustainability of the Hydropower Sector in Lao PDR now makes it possible to ensure that the principles of social and ecological sustainability are fully integrated into all large scale hydropower developments. Thus, it is now possible to replicate some of the experiences obtained from the Nam Theun 2 Project in other hydropower investment projects even though it is not possible to use the Nam Theum project as a standard [27].

It should here be mentioned that hydropower projects in the past did not allocate budget to secure for social and environmental sound sustainability solutions while the newer projects such as Nam Ngum 1 Hydropower Dam, allocated up to 8 % (62 USD million) of the project cost on the matter as an influence of the government policy and law on social and environmental management.

Several studies have been carried out on the economic environment of the relocated households and local communities around the hydropower sites. Most of the surveys indicate that the annual family income has increased approximately by 50%. Besides, the local communities changed their livelihood based on agricultural cultivation to other activities such as fishery, tourism, retail, and other commercial activities. As a result, not only family income has improved, natural environment and livelihood have also positively been influenced.

The following figure shows the average income by zones (2008-2011) for the Theum Hinboun Expansion Project (THXP) [39]

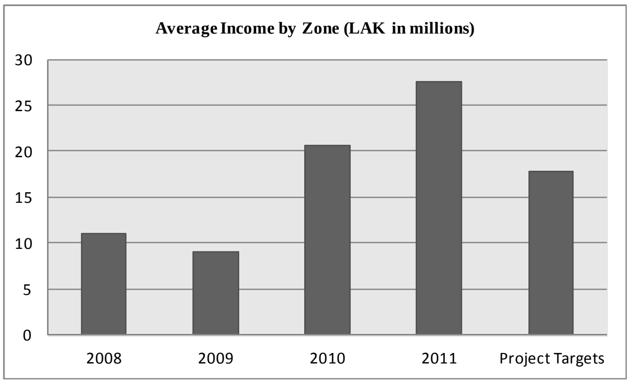

Fig. 2. Average income in all zones covered by the THXP region

Lessons Learnt from resettlement of Theun Hinboun Expansion Project

The planning for large Nam Theun 2 Hydro Power Project was a key factor in terms of introducing a resettlement policy in the Lao PDR. Prior to Nam Theun 2 Project no specific reallocation or resettlement policy was in place. Furthermore, the implementation of hydropower projects was not consistent with donor-funded project requirements for a wide range of studies and standards conditional to financing. Many projects were implemented with low levels of compensation and limited follow-ups. With regard to resettlement, the physical relocation of villages and people has primarily been based on providing the basic essential infrastructure, such as roads, with little long-term support for positive livelihood development. The Nam Theun 2 Project's resettlement Action Plan involved the draft of a Resettlement policy for the whole country. The WB and ADB, as well as other lenders, insisted that the project is prepared and implemented according to their requirements.

A clear policy and institutional structure was required and the legislation needed for this was developed in 2003. The Theun-Hinboun Expansion Project's (THXP) feasibility phase started in 2003 and was prepared in accordance with the new resettlement policy and regulations.

The Theun Hinboun Expansion Project (THXP) is an expansion on the existing Theun - Hinboun Power project (THPP), which was the first private sector Build-Own-Operate-Transfer (BOOT) hydropower development in the county. It is located on the Nam Theun, a major river in the central Lao PDR, approximately 100 kilometres upstream of the confluence of the Mekong and the Nam Theun/Kading. From the Nam Theun basin water flows at a rate of $110m^3$/sec and is diverted through a tunnel to a powerhouse (with a generating capacity of 220 MW) and then discharged through a tailrace canal and regulating pond into the Nam Hai, a tributary of the Nam Hinboun. The dam has a height of 25m and a 197m long overflow weir, creating a head pond which allows 15-million m^3 storage volume). This result is higher water levels along a 24-kilometre stretch of the Nam Theun, but not higher than the natural flood levels. As the dam has no flood zone due to the "run-of-the-river" design no resettlement of the population was required.

Resettlement Planning for THXP

The preparation of the RAP was carried out by consultants in accordance with ADB safeguard policies and requirements and Lao resettlement policy (2003). People involved in this project had the advantage of the completed studies and lessons learnt in preparing such documents from the NT2 project. The Company, THPC, was committed at the start to follow the prescribed guidelines and managed to develop high standards of social and environmental mitigation and sustainable development. The owners (20% Statkraft from Norway, 20% GMS of Thailand and 60% Electricite du Laos) provided funds for early preparation and even prepared the ESIAs before the final financing aspects were in place.

The entitlements for the Resettlement Action plan such as compensation for all forest and crops and other non-removable assets are now important elements A disturbance allowance was also provided together the transportation costs related all goods and commodities when reallocating to new locations. New houses were constructed in close consultation with resettles and communities. Houses between 60m2 and $70m^2$ houses were constructed, and for each family a l800m2 housing plot was provided for vegetable production, fruit trees and small livestock, as well as one hectare for rice production land (potentially irrigated) and ½ hectare for upland crops.

Improved services (schools and health centres) were provided with 3 year health coverage, improved infrastructure - roads, water supply, electricity and community buildings, Technical Assistance for livelihood development. All commitments which resulted in an approximately 50% increase of average income compared to the pre-project incomes.

At Financial Close in October 2008, the Social and Environmental Division (SED) of the THXP had over 100 fulltime and seconded government staff work on consultations, health, social management, infrastructure, agriculture and environmental monitoring programs. Resettlement of the first group of 156 households from the two villages closest to the dam construction site was undertaken from March to May 2009, less than six months after the financial agreements was signed. All the necessary planning had been done well in advance, and many social programs were started and partly implemented before the construction activities for the power plant started and there were other serious commitments to improving lives and livelihood for the involved and affected people. In general, the following parameters were used:

- Flexibility in implementation details based on sound principles and legal requirements;
- Lengthy and detailed consultations with resettlers and host villagers;
- Additional measures for addressing vulnerable groups and small ethnic minorities;
- Livelihood activities started-up immediately after relocation to the new location;
- Completion of compensations and other payments were done as promptly as possible;
- Implementation of a monitoring system of key indicators to show changes and progress each year.

Successful Aspects of Resettlement Implementation

A number of actions were carried out during preparation and implementation that turned out to be successful in achieving goals and positive results. Examples to be explained in this paper will be limited to:

- Preventative measures - Setting up programs prior to construction start up activities can be broadly classified as "preventive measure" as their aim is to avoid potential negative impacts.
- Staffing up – the THXP has the advantage of using existing staff from the first project;
- Participatory approaches - Site Selection Participatory and public approaches take more time and are open-ended by nature, potentially posing and challenge to project development and implementation.
- Establishing procedures and formats. During implementation phase , managers focused on carrying out programs and are applying on system to be in place to enable them to work efficiently and effectively;
- Monitoring approach. THXP was planned with one very important goal in mind: to show that a large hydropower project with resettlement and other impacts can be successfully mitigated and project affected persons could indeed become project beneficiaries [38].

The policy promotes an integrated approach to river basin management with multiple projects on a single river. Cumulative impacts are to be recognized and measures required for their mitigation. Some of the main elements of the policy are a broad definition of project affected people and their right to sustainable development options, free prior and informed consultation, disclosure of project consultation reports, compliance with oversight from third-party agencies, and project revenues to cover the costs of environmental and social safeguards through the Environmental Protection Fund (EPF) established in June 2005 [28].

The Environmental Protection Law stipulates an EPF (2011), which has specialized funding “windows” for the collection, management and distribution of funds from large-scale water developers such as hydropower. Hydropower projects are supposed to contribute a percentage of the revenues to the Environment Protection Fund, which would then distribute the funding to ensure institutional capacity building, environmental and biodiversity conservation programs. Some of revenue from Nam Theun 2 Hydropower Project now flows to the EPF [27]. The fund, however, has not been functioning properly, but the mechanism could potentially serve as a model for direct benefit sharing with affected and involved communities [27]. The establishment of the first Watershed Management Protection Authority in Lao PDR is also a result of the accomplishment of the Nam Theun 2 project. This Authority is responsible for the management and protection of the watershed of the Nam Theun 2 above the reservoir formed by the Nam Theun 2 hydro-electric dam [25].

The Lao EIA process is largely compatible with international guidelines for conducting EIAs. However, there is some unclear division or split of responsibility among various agencies, inadequate human and financial resources and inconsistency of legislation and regulations. In response to these deficiencies the Government has recently promulgated the binding approval of the environmental and social impact assessment (ESIA) and the related Compliance Certificate, as part of the concession acquisition process [27].

The key legal institutions and frameworks are in place in the hydropower sector in Lao PDR, they tend to be constrained by low institutional capacity. Shortage of human resources at key sector regulatory agencies including Water and Resources Environment Administration, Ministry of Energy and Mines and provinces have been a bottleneck for preparing environmental studies and social sustainability surveys in cost-effectiveness way and in compliance with relevant government policies and decrees [27]. There is a need to conduct thorough capacity assessments and prepare capacity building plans and to ensure proper funding for these activities. Comprehensive training activities and implementation of operational practices will be required. There is also a need to develop capacity for operation and maintenance after the concession period ends.

Major gaps remain between the formulation and implementation of legal instruments, and between the establishment and enforcement of rules and regulations. Important issues to be raised are the implementation and enforcement of the existing environmental regulations and building of enforcement and monitoring capacity related to the hydropower sector. Implementation capacity for ESIA procedures needs to be strengthened within Ministry of Natural Resources and Environment and other relevant ministries. Especially, capacity building to monitor the implementation of environmental management and mitigation processes is highly required as well as awareness building of all actors at all levels to protect the environment.

ESIA still frequently fails to influence decision making, like for example, the case of Theun-Hinboun power dam shows [14, 21, 29, and 30]. There is a need to improve environmental governance at the same pace as current trends in foreign direct investments in the hydropower sector. There is also a need to encourage companies and other investors to commit to a high standard of investment policy and socio-environmental performance. By the approval and the use of the new ESIA Decree, ESIA procedures and process will become more transparent, including clear responsibilities of key agencies and project owners; (who is doing what and when?). Also the role of MONRE as the third-party regulating agency for all stages of approval and monitoring need to be strengthened, so it is possible to have clear requirement for social impact assessments, public involvement, and disclosure [27].

What is Lao PDR’s energy roll-out strategy for the next ten years, and why does hydropower play such an important part in the strategy?

The 2 main objectives of power sector development in Lao are: (1) to supply reliable and affordable power to all sectors of the domestic demand. Electrification ratio reached 73% or 756,604 households in 2010, increased by 15% compared to year 1995; The power ratio is expected to reach 80% in 2015 and 90% in 2020; (2) to export excess electricity to provide a source of revenues to fund the economic and social development in country and alleviate poverty.

Installed capacity was 200 MW in 1995 and would be 3,200 MW in 2012, and about 75% of this capacity is devoted for export. Furthermore, it is goal to export 12,500 MW or more than 85% of total installed capacity by 2020, substantially all from new hydropower plants;

Lao PDR chooses hydropower because we have large hydro potentials; hydropower is clean, zero carbon emission and because hydro power is a renewable energy source; hydropower offers more than power generation: No other method of generating electricity can create opportunities for providing water for human consumption and flood control, while generating clean and inexpensive electricity; hydropower is also a non-consumptive use of water solution. Furthermore, the hydropower sector makes contribution of 33% of the GDP in Lao PDR (Wealth and Sustainability – Background Paper on Lao PDR Development Report 2009 by World Bank Group); nobody wants to stay an LDC, and if Laos wants to leave the Least Developed Country list by 2020, what other choices do we have? The only concern is to develop hydropower responsibly, conformed to sustainability criteria and with the Water, Food and Energy nexus approach [34].

If Lao PDR wants to become the battery of SE Asia, what is the biggest challenge it faces in the next decade? And how do we plan to overcome this challenge?

Along with the development of large hydro power projects, we need to expand interconnections to the neighbouring countries to facilitate the present export of power, first on project-by-project basis and, ultimately, realizing the goals of integrated development and operations within Greater Mekong sub-region (GMS) and ASEAN.

The challenges: Interconnected High Voltage transmission infrastructures (network) are required to enable flexibility and reliability in dispatching the energy; in addition to the regulated environment, huge amount of investments are needed – substations and transmission lines – are necessary requiring equally huge amounts of financing resources. Large initial investments are required while long pay-back periods are expected.

Lao Government strategy: Grants and concessionary loans would be preferable to facilitate the development of the power transmission system, but investments by private sectors are also welcome and may also be needed at the initial stages of the interconnections, by individual independent power producers (IPP's) due to the different timeframe of generation projects.

We are furthermore convinced that the GMS/ASEAN power grids would be successful implemented because increased energy interdependence improves the relationship between countries and decreases risk, again improving the general investment climate in the country. The establishment of GMS/ASEAN grids will further support the optimum use of energy resources. Presently, 80% of all power generation in the region is non-renewable, causing many environmental problems such as increased emission of greenhouse gasses, acid rain, toxic wastes, etc. There is a great deal of complementarities in the energy sector in South East Asia; for example, Lao PDR, Vietnam and Thailand could develop and utilize a combination of thermal and hydropower more efficiently through regional agreements. The 12,500 MW or 60,000 GWh of electricity generated using clean and renewable hydropower from Lao PDR will furthermore make an contribution to the reduction of 30-60 mil tons of CO2 emission every year, and the saving of 5 mil toe/y of fossil fuels in this region [34].

Institutional structures for oversight and monitoring include multiple government agencies have to be developed, yet there are evidently major gaps in implementation, some due to unclear and/or overlapping institutional responsibility mandates. There is a need for stronger vertical and horizontal institutional coordination across the government agencies and for building capacity to improve and enhance environmental and social monitoring activities. To develop financially sound hydro projects those are both socially and environmentally sound and will improve the living standards of Lao people.

4.2 Economic Sustainability

There can be no sustainable development and good management without the demonstration of sound and equitable distribution of the economic benefits. For this reason economic considerations are essential in the decision-making processes associated with hydropower projects. The efficient use of economic resources requires that the best options are selected, that the alternatives have been carefully evaluated, and that there are no hidden and unforeseen costs that could emerge in the future.

Currently, energy demand growth has been rapid and the availability of confessional funds and grants of international development banks is not keeping pace with the increasing capital requirements of the power sector. Restructuring and reform of the energy and water sector in many countries including Lao PDR has changed the role of government in decision-making and planning, allowing private investors and corporations taking both financing and ownership roles in these projects [14].

The existing problems and weaknesses in private financing models (planning and procurement) can a negative impact to economic sustainability and effectiveness in Lao PDR. Promotion of independent power producer (IPP) projects in Lao PDR begins with an unsolicited proposal from a sponsor and, from this, a memorandum of understanding is drawn up and a concession ultimately negotiated. Concessions are awarded in the absence of competition after the sponsor has completed technical and environmental studies of the proposed project [31].

The private sector involvement on a significant scale however introduces problems for power planners in managing the uncertainty of IPP commercial operation date (COD) and a means of countering this risk must be found in order to ensure the private sector's role in domestic generation development to be dependable and constructive [31]. Delays in CODs lead to increases in interest accumulated on funds borrowed for construction activities and to delays in revenues accruing to the owner from the completed project [14].

Overall, the failure of project delivery (IPP) can be seen as one of problems related to the practice of awarding mandates for IPP projects as an unsolicited, negotiated transaction based on a BOT modality. Problems related to this approach include the lack of transparency and competition, the failure to filter out projects inconsistent with IPP program objectives, insufficient government control of project development, lack of government's capacity to assess competing development proposals and evaluate associated opportunity costs, a high degree of uncertainty on project outcomes, and unnecessary time commitments for all parties in Lao PDR [27, 31].

Developing new financial models require strong independent regulation and integrated resource planning [32]. There might be a need to establish a regulator to set domestic retail tariffs and negotiate wholesale export tariffs. Currently import tariffs are higher than export tariffs. The establishment of a regulator would mean tariffs could be pre-set before bidding power generation concessions and bidding would therefore be on some other criteria's, perhaps the highest royalty payments. Also, a creation of a centralized Lao power purchasing agency or cooperative that could competitively bid power concessions within Lao PDR and could sell the off-take from some or all Lao power generation projects to domestic and/or foreign power purchasers is needed [31].

For Lao PDR it is important to develop a policy that defines the standard method for determining the fiscal benefits from hydropower projects. The Government needs to ensure that the less direct and longer-term benefits of hydropower projects are not overlooked in the planning process or penalized by short-term financing or tax regime requirements. With new developments, capital and operating costs should be taken into account over the lifetime of a project with a life-cycle assessment of project alternatives forming an integral component of assessment processes. Direct and indirect costs and benefits should be identified, and where possible quantified in monetary terms [33].

The Nam Theun 2 project cost US$1.29 billion, of which US$733 million was used for construction, US$383 million was for the combined financial and advisory costs, another US$94 million for NTPC management, and the remaining US$80 million was for environmental and social cost.

The project development followed the World Bank's guidelines regarding environmental and social practice. Project development regarding the care of the environment and local communities will serve as an example for future projects of a similar nature. The Lao Government will earn annual revenue of US$2 billion throughout the 25 year concession period. The projects assets such as the power plants will be handed over to the Government after the concession ends, under the build operate transfer basis.

In 2012 Nam Theun 2 expects to provide revenue of US$27 million in royalties and dividend to the Lao government. Last fiscal year the company paid US$19 million in resource use charges and dividend. The previous year, the company paid US$5.4 million to the government.

With a strong commitment to the World Bank and the Asian Development Bank, the Lao Government will spend money on poverty reduction, education and healthcare services so that is can achieve the millennium development goals in 2015.

Lao PDR has seen progress in poverty reduction in the country over the past five years. This fiscal year, Laos expects to see a 2% drop in poverty to 22 percent thanks to the booming growth of the mining and hydropower sectors, which have created conditions for people to earn a better living.

Despite the strong economic growth over the past several years, Laos in one of the least developed countries in the world and still relies on foreign assistance.

The country needs about US$700 million as Official Development Assistance (ODA) per year so that it can achieve UN millennium development goals in 2015. The ODA accounts for about 30 to 40 percent of the total investment. The Government highly values the foreign assistance and contribution of development partners in the past but it want to build its own economy and strength. Today, the world economy is volatile, posing challenges for the least developed nations to survive [35].

5. CONCLUSIONS

The Lao country's abundant water resources and mountainous terrain have allowed the Government of Lao to set up a master plan to develop hydropower and export large quantities of hydroelectric energy. Quick growth and steep forecasted size of the energy sector with respect to the economy and Government's revenues will put a lot of pressure to develop institutional environment, policies and fiscal framework to properly use natural resources in Lao PDR's development strategy. When planning and developing hydropower sector investment, ongoing development of the legal, institutional and regulatory environment and strengthening of the institutional capacity and improvements in the commercial position of EDL are issues to be considered in Lao PDR (FREPLA2020, 2009a).

Major problems of Lao hydropower sector relate to lack of capacity and poor institutional environment, such as insufficient quality of environmental and social assessments, ineffective regulatory framework, a lack of transparency, and the failure to conduct comprehensive consultations with all stakeholders. The opportunities and challenges of hydropower development are complex, and ultimately dependent on the resources, skills, and will to invest responsibly, with due regard to economic, environmental and social aspects of sustainable development and management. The governance gap remains a crucial challenge that will increase over time if the government does not take strategic and continued actions to enhance governance and institutional capacity.
There is a need to better assess strategically the hydropower development options for Lao PDR and the use of hydropower development generated revenues to poverty reduction activities. The collective benefits to the country can be maximized if individual hydropower investments are assessed as part of a river basin approach (to understand cumulative hydrological, environmental and social impacts, as well as to increase the economic potential for any given level of impacts) as well as the energy sector development strategy (The World Bank, 2010c, p. 11).

Also there is a need for integrated planning approach which takes into account mining sector development as these sectors are closely interwoven mining sector being dependent on energy sector for its production. The mechanisms for accountability and democratic control and the needs for participatory approaches to hydropower planning and management need to be well recognized and to be strengthened in Lao PDR. Processes and activities related to risk assessment and management need to be established and developed in the energy sector. Currently the risk management lies on private sectors/investors shoulders and as for the risk management the Government has been relying on the multilateral development banks (H.E Somboun Rasasombath, 2010). There is need to conduct research related to this issue and to designate and define clear responsibilities of the risk assessment and management activities to the hydropower sector organizations.

The Lao Government has, during the recent years, put utmost efforts to enhance the integration of social, environmental, and economic benefits to all beneficiaries. It is evidenced that several laws and regulation have been issued, with close monitoring on implementation. The outcome is continuously being improved.

Obviously, sustainable management of hydropower can be achieved by balanced consideration of environmental, economical and social factors. The main goal of sustainable management of hydropower is to maintain adequate renewable hydro resources for sustainable electric power generation, and hence, to ensure sustainable revenue for the country. Besides, public involvement and participation, benefit sharing, setup workable institutional support and mechanism are also among the crucial factors for sustainable management of hydropower.

Lao PDR can and should definitely use its large hydropower advantages but should also learn a lot from other countries in relation to development of hydropower and from past mistakes. The country can draw on the lessons that are emerging from the Nam Theun 2 Project and Theun Hinboun Expansion Project which can generally provide a best practice example in socio-economic and environmental management of hydropower projects

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APPENDIX

Table A1. The existing and planning hydropower projects for EdL

No	Name of Project	Installed Capacity MW	Status	
			Progress	Commercial Operation
1	Nam Dong	1	In Operation	1970
2	Selabam	5	In Operation	1970
4	Se Xet	45	In Operation	1990
5	Nam Ko	1.5	In Operation	1996
3	Nam Ngum 1	155	In Operation	1997
6	Nam Leuk	60	In Operation	2000
7	Nam Mang 3	40	In Operation	2004
8	Se Xet 2	76	In Operation	2009
9	Nam Xong (Expansion)	6	Plan	
10	Selabam (Expansion)	7.7	Plan	
11	Se Xet 3	23.96	Plan	
12	Nam Ngum 1 (Expansion)	40	Under Constn.	
13	Nam Boun 2	15	Plan	
14	Viengphouka (Fire coal)	150	Plan	
15	Houay Lamphan Gnai	88	Under Constn.	
16	Kangsuaten	45	Plan	
17	Se Xet 4	8	Plan	
18	Nam Hinboun 1	40	Plan	
19	Nam Khan 2	60	Under Constn.	
20	Nam Khan 3	60	Plan	
21	Nam Chainh	100	Plan	
22	Nam Phark	30	Plan	

Table A2. Existing and planning IPPs in Lao PDR

No	Name of Project	Installed capacity (MW)	Annual Average Energy (GWh/y)	Status	
				Progress	Commercial Operation
1	Theun-Hinboun	220	1560	In Operation	1998
2	Houay Ho	152	450	In Operation	1999
3	Nam Lik 1-2	100	435	In Operation	2010
4	Nam Theun 2	1080	6000	In Operation	2010
6	Nam Ngum 2	615	2300	In Operation	IOD 2011 COD 2012
7	Xekaman 3	250	982.88	• CA Signed 4/1/2006	2012
8	Nam Ngum 5	120	507	• CA Signed 10/4/2007	2012

9	Theun Hinboun Expansion	280	4563	• CA Signed 27/8/2008	2012
10	Tad Salen	3.2	17	• CA Signed 3/2/2009	2012
11	Hongsa Coal-Fired	1878	12582	• CA Signed 3/11/2009	2015
12	Xayaburi	1285	5990	• CA Signed 29/10/2010	2019
13	Xekaman 1	322	1098	• CA Signed 10/2/2011	2015
14	Nam Long	5	37	• CA Signed 21/3/2011	2013
15	Nam Sim	8	34	• CA Signed 13/06/2011	2015
16	Nam Ngiep 2	180	723	• CA Signed 18/8/2011	2015
17	Nam Ngum 3	460	2047	• PDA Signed 15/11/1997	2018
18	Nam Theun 1	523	2016	• PDA Signed 28/11/2004	
19	Nam Ngiep 1	290	1507	• PDA Signed 27/4/2004	2018
20	Xe Katam	61	380	• PDA Signed 20/12/2007	2016
21	Nam Ou 1-7 (Cascade)	1156	5064	• PDA Signed 15/10/2007	2016
22	Donsahong (Mekong)	240	1756	• PDA Signed 13/2/2008	
23	Nam Mo	120	516	• PDA Signed 30/3/2008	2015
24	Nam Lik 1	60	256	• PDA Signed 8/4/2008	
25	Nam Sane 3	65	440	• PDA Signed 19/6/2008	
26	Nam Kong 1	75-150	469-563	• PDA Signed 23/6/2008	
27	Sekong 4	300-600	1901-2119	• PDA Signed 23/6/2008	
28	Xepian-Xenamnoy	390	1788	• PDA Signed 14/11/2008	2018
29	Se Kong 5	330	1613	• PDA Signed 19/6/2009	
30	Nam Phak	45	307	• PDA Signed 6/11/2009	
31	Nam Beng	34	137	• PDA Signed 10/3/2010	
32	Nam Mang 1	57	201	• PDA Signed 20/5/2010	2015
33	Nam Tha 1	168	721	• PDA Signed 16/6/2010	
34	Nam Seuang 1	63	320	• PDA Signed 11/8/2010	
35	Nam Seuang 2	141	718	• PDA Signed 11/8/2010	
36	Nam Pha	130	594	• PDA Signed 20/8/2010	
37	Phou Ngoy (Mekong)	651	3278	• PDA Signed 7/12/2010	
38	Sanakham (Mekong)	660		• PDA Signed 27/12/2010	
39	Pakbeng (Mekong)	855	4846	• PDA Signed 27/12/2010	
40	Xenamnoy 1	15	100	• PDA Signed 28/1/2011	
41	Nam Kong 2	66	263	• PDA Signed 16/03/2011	2014
42	Nam Sum 1	102	1015	• PDA Signed 19/09/2011	2016
43	Nam Sum 3	186	244	• PDA Signed 19/09/2011	2016
44	Nam Phay	60	429	• PDA Signed 20/12/2011	
45	Nam Ham	3.5	14	• MOU Signed 6/4/2005	
46	Xe Neua	53	209	• MOU Signed 16/5/2006	
47	Xekaman 4	80	315	• MOU Signed 19/12/2006	
48	Nam Feuang	28	113	• MOU Signed 3/4/2007	
49	Nam Bak 1	160	744	• MOU Signed 11/4/2007	
50	Nam Bak 2	40	205	• MOU Signed 11/4/2007	
51	Pak Lay (Mekong)	1320	5948	• MOU Signed 11/6/2007	

52	Louangprabang (Mekong)	1410	7380	• MOU Signed 13/10/2007	
53	Dak Emeule	130	525	• MOU Signed 8/1/2008	
54	Se kong 3 (3 A)	105	410	• MOU Signed 29/1/2008	
55	Se kong 3(3 B)	100	393	• MOU Signed 29/1/2008	
56	Ban Koum (Mekong)	1872	8433	• MOU Signed 25/3/2008	
57	Nam Ngum 4	220	822	• MOU Signed 30/3/2008	
58	Xebanghieng 1	50	197	• MOU Signed 25/11/2008	
59	Xebanghieng 2	52	198	• MOU Signed 25/11/2008	
60	Nam Phoun	74		• MOU Signed 5/12/2008	
61	Nam Ma (1, 1A, 2, 2A, 3)	149	605.1	• MOU Signed 30/12/2008	
62	Thakho	50	360	• MOU Signed 17/3/2009	
63	Houay Champy	5		• MOU Signed 26/5/2009	
64	Nam Kong 3	45	170	• MOU Signed 31/8/2009	
65	Nam Neun	65		• MOU Signed 8/10/2009	
66	Nam Pot	15	70.5	• MOU Signed 26/11/2009	
67	Nam Ngiep Muang Mai	38		• MOU Signed 25/2/2010	
68	Nam Mouan	124	524	• MOU Signed 26/2/2010	
69	Nam Mo 1	60-80		• MOU Signed 4/3/2010	
70	Xepian-Houay Soy	100	250	• MOU Signed 30/3/2008	
71	Se Kong Downstream	80		• MOU Signed 26/8/2010	
72	Nam Phouan	60		• MOU Signed 24/9/2010	
73	Nam Poui	60	294	• MOU Signed 6/10/2010	
74	Nam Ang Thabeng	30		• MOU Signed 15/03/2011	
75	Xelanong 1	80		• MOU Signed 28/06/2011	
76	Nam Et 1,2,3	420		• MOU Signed /2011	
77	Nam Nga	80		• MOU Signed 11/11/2011	

Augmented Lagrange Hopfield Network for Combined Economic and Emission Dispatch with Fuel Constraint

Vo Ngoc Dieu, Nguyen Phuc Khai, and Le Quoc Uy

Abstract— *This paper proposes an augmented Lagrange Hopfield network (ALHN) for solving combined economic and emission dispatch (CEED) problem with fuel constraint. In the proposed ALHN method, the augmented Lagrange function is directly used as the energy function of continuous Hopfield neural network (HNN), thus this method can properly handle constraints by both augmented Lagrange function and sigmoid function of continuous neurons in the HNN. For dealing with the bi-objective economic dispatch problem, the slope of sigmoid function in HNN is adjusted to find the Pareto-optimal front and then the best compromise solution for the problem will be determined by fuzzy-based mechanism. The proposed method has been tested on many cases and the obtained results are compared to those from other methods available the literature. The test results have shown that the proposed method can find good solutions compared to the others for the tested cases. Therefore, the proposed ALHN could be a favourable implementation for solving the CEED problem with fuel constraint.*

Keywords— **Augmented Lagrange Hopfield network, combined economic and emission dispatch.**

NOMENCLATURE

a_i, b_i, c_i — emission coefficients for thermal unit i

d_i, e_f, f_i — fuel cost coefficients for thermal unit i

B_{ij}, B_{0i}, B_{00} — transmission loss formula coefficients

F_{ik} — fuel delivery for thermal unit i during subinterval k, in tons

F_i^{min}, F_i^{max} — lower and upper fuel delivery limits for thermal unit i, in tons

M — number of subintervals of scheduled period

N — total number of thermal units;

P_{Dk} — load demand of the system during subinterval k, in MW

P_{Lk} — transmission loss of the system during subinterval k, in MW

P_{ik} — output power of thermal unit i during subinterval k, in MW

P_i^{min}, P_i^{max} — lower and upper generation limits of thermal unit i, in MW

Q_{ik} — fuel consumption function of thermal unit i in subinterval k, in tons/h

t_k — duration of subinterval k, in hours

X_{i0} — initial fuel storage for unit i, in tons

X_{ik} — fuel storage for unit i during subinterval k, in tons

X_i^{min}, X_i^{max} — lower and upper fuel storage limits for thermal unit i, in tons

$V_{p,ik}$ — output of continuous neuron representing for output power P_{ik}

$V_{f,ik}$ — output of continuous neuron representing for fuel delivery F_{ik}

$V_{x,ik}$ — output of continuous neuron representing for fuel storage X_{ik}

$V_{\lambda,k}$ — output of multiplier neuron associated with power balance constraint

$V_{\gamma,k}$ — output of multiplier neuron associated with fuel delivery constraint

$V_{\eta,ik}$ — output of multiplier neuron associated with fuel storage constraint

$U_{p,ik}, U_{f,ik}, U_{x,ik}$ — inputs of continuous neurons corresponding to the outputs $V_{p,ik}$, $V_{f,ik}$ and $V_{x,ik}$, respectively

$U_{\lambda,k}, U_{\gamma,k}, U_{\eta,ik}$ — inputs of multiplier neurons corresponding to the outputs $V_{\lambda,k}$, $V_{\gamma,k}$ and $V_{\eta,ik}$, respectively

ΔP_k — power balance constraint error in subinterval k, in MW

ΔF_k — fuel delivery constraint error in subinterval k, in tons

ΔX_{ik} — fuel storage constraint error for unit i during subinterval k, in tons

$\Delta V_{p,ik}, \Delta V_{f,ik}, \Delta V_{x,ik}$ — iterative errors of continuous neurons

σ — slope of sigmoid function of continuous neurons

$\alpha_p, \alpha_f, \alpha_x$ — updating step sizes for continuous neurons

$\alpha_\lambda, \alpha_\gamma, \alpha_\eta$ — updating step sizes for multiplier neurons

$\varphi_{0i}, \varphi_{1i}, \varphi_{2i}$ — fuel consumption coefficients for thermal unit i

$\lambda_k, \gamma_k, \eta_{ik}$ — Lagrangian multipliers associated with power balance, fuel delivery and fuel storage constraints, respectively

$\beta_{\lambda,k}, \beta_{\gamma,k}, \beta_{\eta,sk}$ — penalty factors associated with power balance, fuel delivery and fuel storage constraints, respectively

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1. INTRODUCTION

Economic dispatch with fuel constraint is an important part of utility for operation and planning since it is a complex problem with a long range of time periods and a large set of constraints and variables. The fuel used by a thermal generating unit may be obtained from different contracts at different prices. The fuel contracts are generally under a take-or-pay agreement including both maximum and minimum limits on delivery of fuel to generating units over life of the contract. The fuel storage for units is usually within a specified limit to allow for inaccurate load forecasts and the inability to deliver on time of suppliers [1]. On the other hand, thermal generating units generate toxic gases during power production due to fossil fuels and this is also considered as a source of environment pollution [2]. With recently increasing concern on environment impact of power generation, the power generation dispatch is required to reduce the emission level while meeting load demand [3]. However, both the fuel cost and emission level conflict together since the pollution minimization will lead to maximizing the fuel cost and vice versa. Therefore, they both must be simultaneously considered to attain a practical compromise operation and this is termed combined economic and emission dispatch (CEED) problem. For solving this problem, one usually finds a set of compromise solutions by simultaneously optimizing all objectives to form a Pareto-optimal front which represents the tradeoffs among conflicting objective functions.

The objective of the CEED problem with fuel constraint is to minimize both total fuel cost and emission from thermal units while satisfying power balance, fuel delivery, fuel storage constraints together with fuel delivery, fuel storage, and generator operating limits. The schedule time horizon for this problem can be decomposed into long-term (weeks to year) [4], short-term (days to week) [5], daily (hours to day) [6], and real-time (minutes to hour) [7] problems. In the long-term schedule problem, the schedule time is divided into sub-periods (months or weeks) to obtain optimal fuel use strategy.

The economic dispatch with fuel constraint for thermal units have been investigated in [7] using linear programming (LP) and network flow programming (NFP). In the LP method [8], the total time period is divided into discrete time increments and the objective function is made up a sum of linear functions where each of function is a function of one or more variables from one step time. In the NFP method [9], the input/output characteristics of generating units can be linear or non-linear which will form linear or non-linear network. For the non-linear network, the problem is solved as a sequence of linear networks with artificial limits calculated from the current solution of the linear network and used for calculating the next solution of the linear network. Nonetheless, these methods suffer difficulties in solving optimization problems. The computation efforts in the NFP will drastically increase when there exist some convex branches in the flow network whereas LP requires linearization of objectives and constraints. On the other hand, the CEED problem has been attracted several researchers. Conventional methods have been applied for solving the problem such as Newton-Raphson (NR) method [10], linear programming (LP) [11], Lagrangian relaxation (LR) method [12], etc. The advantage of these methods is that they can quickly find optimal solution for a problem. However, they suffer some difficulties when dealing with complex and large-scale nonlinear problems such as matrix inversion in NR method, linearization in LP method and duality gap in LR method. For dealing with more complicated problems, several artificial intelligent based methods have been used such as genetic algorithm (GA) [13], evolutionary programming (EP) [14], differential evolution (DE) **Error! Reference source not found.**, and particle swarm optimization (PSO) [16][17]. These population based search methods are suitable for finding near optimal solution for non-convex complicated problems. However, for large-scale problems, these methods become very slow in finding solution and the near optimal solution is not always obtained. Neural networks are also popular for solving the CEED problem [18], [19]. Hopfield neural network (HNN) is the most popular neural network applied to optimization problems and has been successfully applied to the CEED dispatch problem with fuel constraint [19]. Though the HNN can easily handle maximum and minimum constraints for continuous variables based on a sigmoid function, its formulation still suffers some difficulties such as constraint linearization, parameter selection associated with energy function that may lead to local optima if they are not precisely chosen, and map from the problem to the HNN.

In this paper, an augmented Lagrange Hopfield network (ALHN) is proposed for solving combined economic dispatch with fuel constraint. In the proposed ALHN method, the augmented Lagrange function is directly used as the energy function of continuous Hopfield neural network (HNN), thus this method can properly handle constraints by both augmented Lagrange function and sigmoid function of continuous neurons in HNN. For dealing with the bi-objective economic dispatch problem, the slope of sigmoid function in HNN is adjusted to find the Pareto-optimal front and then the best compromise solution for the problem will be determined by fuzzy-based mechanism. The proposed method has been tested on three systems with many cases considered and the obtained results are compared to those from other methods available the literature including recursive approach (RA) [24], simplified recursive approach (SRA) [25], Newton Raphson (NR) [10], fuzzy logic controlled genetic algorithm (FCGA) [13], analytical strategy (AS) [26], multi-objective chaotic particle swarm optimization (MOCPSO) [16], multi-objective chaotic ant swarm optimization (MOCASO) [17].

The remaining organization of this paper is follows. Section 2 addresses the formulation of the combined economic dispatch problem with fuel constraint. Augmented Lagrange Hopfield neural network implement for the problem is described in Section 3. Numerical results are presented in Section 4. Finally, the conclusion is given.

2. PROBLEM FORMULATION

Assuming that the entire schedule time horizon is divided into M subintervals each having a constant load demand P_{Dk} and that all generating units are available and remain on-line for M subintervals. The objective is to simultaneously minimize generation cost F_1 and emission level F_2 of generating units over the M subintervals such that the constraints for power balance, fuel delivery and fuel storage for any given subinterval as well as maximum-minimum fuel delivery, fuel storage, and generator operating constraints for each generating unit are satisfied.

We propose an h-factor to combine generation F_1 and emission level F_2 of generating units.

Mathematically, the problem formulation for a system having N thermal generating units scheduled in M subintervals is as follows [19]:

$$\text{Min } \{F_1 + h.F_2\} \tag{1}$$

where F_1 and F_2 respectively representing the total fuel cost and emission functions are defined based on the quadratic function as follows:

$$F_1 = \sum_{k=1}^{M}\sum_{i=1}^{N} t_k \left(a_i + b_i P_{ik} + c_i P_{ik}^2\right) \tag{2}$$

$$F_2 = \sum_{k=1}^{M}\sum_{i=1}^{N} t_k \left(d_i + e_i P_{ik} + f_i P_{ik}^2\right) \tag{3}$$

The h-factor is calculated as follows:

$$h_i = \frac{a_i + b_i P_i^{\max} + c_i \left(P_i^{\max}\right)^2}{d_i + e_i P_i^{\max} + f_i \left(P_i^{\max}\right)^2} \tag{4}$$

subject to

(a) Power balance constraints

The total power supply from the generating units must be sufficient supplying to forecasted load demand of the system and power transmission loss for the whole schedule time horizon:

$$\sum_{i=1}^{N} P_{ik} - P_{Lk} - P_{Dk} = 0\ ;\ k = 1,\ldots, M \tag{5}$$

where system power loss is determined by the Kron's formula [8] as follows:

$$P_{Lk} = \sum_{i=1}^{N}\sum_{j=1}^{N} P_{ik} B_{ij} P_{jk} + \sum_{i=1}^{N} B_{0i} P_{ik} + B_{00} \tag{6}$$

(b) Fuel delivery constraint

The total fuel delivery to the generating units must satisfy their demand during the considered schedule time horizon:

$$\sum_{i=1}^{N} F_{ik} - F_{Dk} = 0\ ;\ k = 1, \ldots, M \tag{7}$$

(c) Fuel storage constraint

The fuel storage for the generating units must be sufficient for their consumption during the considered schedule time horizon:

$$X_{ik} = X_{ik-1} + F_{ik} - t_k Q_{ik}\ ;\ i = 1, \ldots, N;\ k = 1, \ldots, M \tag{8}$$

where the fuel consumption of generating units are expressed as a function of power generation:

$$Q_{ik} = \varphi_{0i} + \varphi_{1i} P_{ik} + \varphi_{2i} P_{ik}^2 \tag{9}$$

(d) Generator operating limits

The power outputs from the generators are limited by their capacity of generation:

$$P_i^{\min} \le P_{ik} \le P_i^{\max}\ ;\ i = 1, \ldots, N;\ k = 1, \ldots, M \tag{10}$$

(e) Fuel delivery limits

The fuel delivery to generating units is limited by the capacity of suppliers:

$$F_i^{\min} \le F_{ik} \le F_i^{\max}\ ;\ i = 1, \ldots, N;\ k = 1, \ldots, M \tag{11}$$

(f) Fuel storage limits

The fuel storage for generating units is limited by the capacity of the storages:

$$X_i^{\min} \le X_{ik} \le X_i^{\max}\ ;\ i = 1, \ldots, N;\ k = 1, \ldots, M \tag{12}$$

The fuel storage at subinterval k in (7) can be rewritten in terms of initial fuel storage as follows:

$$X_{ik} = X_{i0} + \sum_{l=1}^{k}\left(F_{il} - t_l Q_{il}\right) \tag{13}$$

in which, the initial fuel storage X_{i0} is given.

3. AUGMENTED LAGRANGE HOPFIELD NETWORK IMPLEMENTATION

For implementation of the bi-objective problem in ALHN, the two objectives are combined in the Lagrangian function which is used as energy function in HNN. By adjusting the sigmoid slope of continuous neurons the obtained corresponding solutions will form a Pareto-optimal front and then the best compromise solution will be determined by fuzzy-based mechanism [20]. The principle of multi-objective optimization and the fuzzy-based mechanism are given in Appendix.

The augmented Lagrange function L of the problem is formulated as follows

$$L=\sum_{k=1}^{M}\sum_{i=1}^{N}t_k\left[ah_i+bh_iP_{ik}+ch_iP_{ik}^2\right]$$
$$+\sum_{k=1}^{M}\left[\lambda_k\left(P_{Lk}+P_{Dk}-\sum_{i=1}^{N}P_{ik}\right)+\frac{1}{2}\beta_{\lambda,k}\left(P_{Lk}+P_{Dk}-\sum_{i=1}^{N}P_{ik}\right)^2\right]$$
$$+\sum_{k=1}^{M}\left[\gamma_k\left(\sum_{i=1}^{N}F_{ik}-F_{Dk}\right)+\frac{1}{2}\beta_{\gamma,k}\left(\sum_{i=1}^{N}F_{ik}-F_{Dk}\right)^2\right]$$
$$+\sum_{k=1}^{M}\sum_{i=1}^{N}\left[\begin{array}{l}\eta_{ik}\left(X_{ik}-X_{i0}-\sum_{l=1}^{k}\left(F_{il}+t_lQ_{il}\right)\right)+\\+\frac{1}{2}\beta_{\eta,ik}\left(X_{ik}-X_{i0}-\sum_{l=1}^{k}\left(F_{il}+t_lQ_{il}\right)\right)^2\end{array}\right] \quad (14)$$

where: ah_i, bh_i, ch_i are defined from the h-factor: $ah_i = a_i + h_i.d_i$; $bh_i = b_i + h_i.e_i$; $ch_i = c_i + h_i.f_i$;

To represent in augmented Lagrange Hopfield neural network, $3N$xM continuous neurons and ($N+2$)xM multiplier neurons are required. The energy function E of the problem is formulated based on the augmented Lagrangian function in terms of neurons as follows.

$$E=\sum_{k=1}^{M}\sum_{i=1}^{N}t_k\left[ah_i+bh_iV_{p.ik}+ch_iV_{p,ik}^2\right]$$
$$+\sum_{k=1}^{M}\left[V_{\lambda k}\left(P_{Lk}+P_{Dk}-\sum_{i=1}^{N}V_{p,ik}\right)+\frac{1}{2}\beta_{\lambda k}\left(P_{Lk}+P_{Dk}-\sum_{s=1}^{N}V_{p,ik}\right)^2\right]$$
$$+\sum_{k=1}^{M}\left[V_{\gamma k}\left(\sum_{i=1}^{N}V_{f,ik}-F_{Dk}\right)+\frac{1}{2}\beta_{\gamma,k}\left(\sum_{s=1}^{N}V_{f,ik}-F_{Dk}\right)^2\right]$$
$$+\sum_{k=1}^{M}\sum_{i=1}^{N}\left[\begin{array}{l}V_{\eta,ik}\left(V_{x,ik}-X_{i0}-\sum_{l=1}^{k}\left(V_{f,il}+t_lQ_{il}\right)\right)+\\+\frac{1}{2}\beta_{\eta,ik}\left(V_{x,ik}-X_{i0}-\sum_{l=1}^{k}\left(V_{f,il}+t_lQ_{il}\right)\right)^2\end{array}\right]$$
$$+\sum_{k=1}^{M}\sum_{i=1}^{N}\left(\int_0^{V_{p,ik}}g^{-1}(V)dV+\int_0^{V_{f,ik}}g^{-1}(V)dV+\int_0^{V_{x,ik}}g^{-1}(V)dV\right) \quad (15)$$

In (14), the sums of integral terms are Hopfield terms where their global effect is a displacement of solutions toward the interior of the state space [21].

The dynamics of augmented Lagrange Hopfield network for updating neuron inputs are defined as follows.

$$\frac{dU_{p,ik}}{dt}=-\frac{\partial E}{\partial V_{p,ik}} \quad (16)$$

$$\frac{dU_{f,ik}}{dt}=-\frac{\partial E}{\partial V_{f,ik}} \quad (17)$$

$$\frac{dU_{x,ik}}{dt}=-\frac{\partial E}{\partial V_{x,ik}} \quad (18)$$

$$\frac{dU_{\lambda,k}}{dt}=+\frac{\partial E}{\partial V_{\lambda,k}} \quad (19)$$

$$\frac{dU_{\gamma,k}}{dt}=+\frac{\partial E}{\partial V_{\gamma,k}} \quad (20)$$

$$\frac{dU_{\eta,ik}}{dt}=+\frac{\partial E}{\partial V_{\eta,ik}} \quad (21)$$

The inputs of neurons are updated based on their dynamics as follows:

$$U_{p,ik}^{(n)}=U_{p,ik}^{(n-1)}-\alpha_p\frac{\partial E}{\partial V_{p,ik}} \quad (22)$$

$$U_{f,ik}^{(n)}=U_{f,ik}^{(n-1)}-\alpha_f\frac{\partial E}{\partial V_{f,ik}} \quad (23)$$

$$U_{x,ik}^{(n)}=U_{x,ik}^{(n-1)}-\alpha_x\frac{\partial E}{\partial V_{x,ik}} \quad (24)$$

$$U_{\lambda,k}^{(n)}=U_{\lambda,k}^{(n-1)}+\alpha_\lambda\frac{\partial E}{\partial V_{\lambda,k}} \quad (25)$$

$$U_{\gamma,k}^{(n)}=U_{\gamma,k}^{(n-1)}+\alpha_\gamma\frac{\partial E}{\partial V_{\gamma,k}} \quad (26)$$

$$U_{\eta,ik}^{(n)}=U_{\eta,ik}^{(n-1)}+\alpha_\eta\frac{\partial E}{\partial V_{\eta,ik}} \quad (27)$$

The outputs of continuous neurons representing for output power, fuel delivery and fuel storage of power plants are calculated from on their inputs by a sigmoid function [22]:

$$V_{p,ik}=g(U_{p,ik})=\left(\frac{P_i^{\max}-P_i^{\min}}{2}\right)\left[1+\tanh\left(\sigma U_{p,ik}\right)\right]+P_i^{\min} \quad (28)$$

$$V_{f,ik}=g(U_{f,ik})=\left(F_i^{\max}-F_i^{\min}\right)\left(\frac{1+\tanh\left(\sigma U_{f,ik}\right)}{2}\right)+F_i^{\min} \quad (29)$$

$$V_{f,ik}=g(U_{f,ik})=\left(F_i^{\max}-F_i^{\min}\right)\left(\frac{1+\tanh\left(\sigma U_{f,ik}\right)}{2}\right)+F_i^{\min} \quad (30)$$

where σ determines the shape of the sigmoid function. The shape of the sigmoid function is shown in Fig. 1.

The outputs of multiplier neurons representing Lagrangian multipliers are determined by a transfer function:

$$\mathrm{V}_{\lambda,k}=g(U_{\lambda,k})=U_{\lambda,k} \quad (31)$$

$$\mathrm{V}_{\gamma,k}=g(U_{\gamma,k})=U_{\gamma,k} \quad (32)$$

$$\mathrm{V}_{\eta,ik}=g(U_{\eta,ik})=U_{\eta,ik} \quad (33)$$

The proof of convergence of the ALHN method is given Appendix.

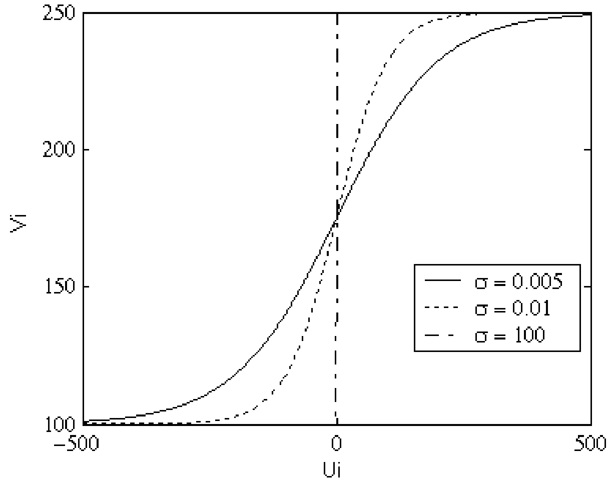

Fig. 1. Sigmoid function with different slopes

3.1 Selection of parameters

All positive parameters in the ALHN model have to be selected in advance including slope of sigmoid function and updating step sizes for neurons and penalty factors associated with constraints. These parameters are selected by experiments and the proper parameters will lead to fast convergence of the network. Among the parameters, the value of σ has directly effect on the priority of objectives in the problem. If σ is greater than 1, the fuel objective is more important than the emission one. In contrast, if σ is smaller than 1, the emission objective is more important. Therefore, the non-dominated solutions for the problem will be obtained by adjusting the value of σ from smaller than 1 to very large values. The penalty factors associated with all constraints are equally chosen and usually fixed to a small value. The other parameters including α_f, α_x, α_γ and α_η will be tuned depending on the considered problem. It is observed that the larger the values of these parameters, the closer the system act to being a discrete system, producing values at the upper and lower limits of each neuron. On the contrary, the smaller the values of them, the slower the convergence of the network. For simplicity, the values of α_f and α_x can be equally chosen. It is similar manner for α_γ and α_η.

3.2 Initialization

The algorithm requires initial conditions for inputs and outputs of all neurons. In this paper, the initial outputs of neurons are selected as follows.

For the continuous neurons representing for power output and fuel delivery of units, their outputs are initiated by "mean distribution" [23]:

$$V_{p,ik}^{(0)} = P_{Dk} \frac{P_i^{\max}}{\sum_{i=1}^{N} P_i^{\max}} \tag{34}$$

$$V_{f,ik}^{(0)} = F_{Dk} \frac{F_i^{\max}}{\sum_{i=1}^{N} F_i^{\max}} \tag{35}$$

For the neurons representing for fuel storage of power plants, their outputs are initiated at the medium value between the maximum and minimum values of fuel storage:

$$V_{x,ik}^{(0)} = \left(X_i^{\max} + X_i^{\min}\right)/2 \tag{36}$$

For the multiplier neurons associated with power balance constraint, their outputs are initialized by mean values as follows:

$$V_{\lambda k}^{(0)} = \frac{1}{N}\sum_{i=1}^{N} \frac{t_k\left(b_i + 2c_i V_{p,ik}^{(0)}\right) + t_k\left(e_i + 2f_i V_{p,ik}^{(0)}\right)}{1 - \frac{\partial P_{Lk}}{\partial V_{p,ik}}} \tag{37}$$

The outputs of other multiplier neurons are initiated from zeros. The inputs of all neurons are calculated corresponding to their outputs via the inversion of corresponding sigmoid and transfer functions.

3.3 Stopping criteria

The algorithm of the ALHN will be terminated when either the maximum error Err_{max} including both constraint and iterative errors is lower than a predefined tolerance ε or maximum number of iterations N_{max} is reached.

The constraint and iterative errors at iteration n are calculated as follows.

$$\Delta P_k^{(n)} = \left| P_{Dk} + P_{Lk} - \sum_{i=1}^{N} V_{p,ik}^{(n)} \right| \tag{38}$$

$$\Delta F_k^{(n)} = \left| \sum_{i=1}^{N} V_{f,ik}^{(n)} - F_{Dk} \right| \tag{39}$$

$$\Delta X_{ik}^{(n)} = \left| V_{x,ik}^{(n)} - X_{i0} - \sum_{l=1}^{k}\left(V_{f,il}^{(n)} + t_l Q_{il}\right) \right| \tag{40}$$

$$\Delta V_{p,ik}^{(n)} = \left| V_{p,ik}^{(n)} - V_{p,ik}^{(n-1)} \right| \tag{41}$$

$$\Delta V_{f,ik}^{(n)} = \left| V_{f,ik}^{(n)} - V_{f,ik}^{(n-1)} \right| \tag{42}$$

$$\Delta V_{x,ik}^{(n)} = \left| V_{x,ik}^{(n)} - V_{x,ik}^{(n-1)} \right| \tag{43}$$

The maximum error of the model is determined:

$$Err_{\max}^{(n)} = \max\left\{\Delta P_k^{(n)}, \Delta F_k^{(n)}, \Delta X_{ik}^{(n)}, \Delta V_{p,ik}^{(n)}, \Delta V_{f,ik}^{(n)}, \Delta V_{x,ik}^{(n)}\right\} \tag{44}$$

3.3 Overall procedure

Overall procedure of ALHN for solving the CEED problem with fuel constraint is as follows:

Step 1: Select parameters for the network as in Section 3.1 and choose stopping criteria as in Section

3.3.

Step 2: Initialize inputs and outputs for all neurons as in Section 3.2.

Step 3: Set number of iteration $n = 1$.

Step 4: Calculate dynamics of neurons from equations (16) - (21).

Step 5: Update inputs of neurons from equations (22) - (27).

Step 6: Calculate outputs of neurons from equations (28) - (33).

Step 7: Calculate maximum error as in Section 3.3.

Step 8: If $Err_{max} > \varepsilon$ and $n < N_{max}$, $n = n + 1$ and return to Step 4.

Step 9: Calculate total cost and emission, and stop.

4. NUMERICAL RESULTS

The proposed ALHN is tested on six-unit and three-plant systems without fuel constraint and a five-unit system with fuel constraint. The algorithm of ALHN is coded in Matlab platform and run on a 2.1 GHz with 2 GB RAM PC. For stopping criteria, the maximum tolerance ε is set to 10^{-4}.

4.1 Case 1: Six-unit system neglecting fuel constraint

The test system from [24] includes six units supplying to a load demand of 900 MW.

4.1.1 Case 1a: Neglecting power loss

When power loss is neglected, the total power generation is balanced to load demand. Three cases are considered in this cases including best economic dispatch, best emission dispatch and combined economic and emission dispatch.

Table 1 shows a comparison of best compromise solution from ALHN to that from RA method and simplified RA (SRA) method [25]. To find the best compromise solution by ALHN, a Pareto-optimal front is obtained first as shown in Fig. 2 and then the fuzzy-based mechanism is used. For comparison of the best compromise solution among the methods, a price penalty factor (PPF) method [18] is used as in Table 1. The explanation and calculation of PPF are given Appendix.

For the cases with single objective optimization, the total cost and emission amount by the proposed method are closed to those from RA method. However, for the case of best compromise solution, the total equivalent cost from the proposed ALHN is less than that from RA method.

Table 1: Comparison of best compromise solution for Case 1a

	RA [24]	SRA [25]	ALHN
Fuel cost ($/h)	46,131.80	46,131.80	46,191.32
Emission (kg/h)	679.241	679.241	676.4765
Emission PPF ($/kg)	44.7880	44.7880	44.7880
Equiv. cost of emission ($/h)	30,421.85	30,421.85	30,298.03
Total equiv. cost ($/h)	76,554.65	76,554.65	76,489.35

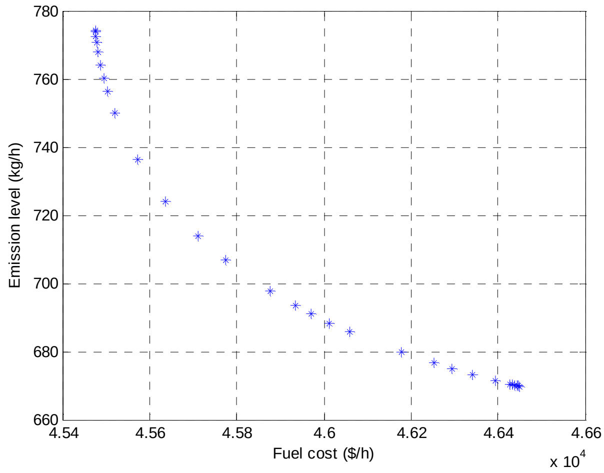

Fig. 2. Pareto-optimal front for fuel cost and emission from Case 1a

4.1.2 Case 1b: Considering power loss

When power loss is included, the total power generation is balanced to load demand plus power loss. In this case, three load demands are considered including 500 MW, 700 MW, and 900 MW. Table 2 shows the comparison of best compromise solutions from the proposed method to those from NR [10] and FCGA methods. The Pareto-optimal fronts for fuel cost and emission corresponding to the load demands are given in Figs. 3. For all the compared cases in Tables 2, the proposed method can find better solutions in terms of less total costs and emission levels for single objective problems and less total equivalent costs for CEED than the others.

4.2 Case 2: Three-plant system neglecting fuel constraint

The test system has three plants with six generating units supplying to a total load demand of 900 MW as shown in **Error! Reference source not found.**. The unit data is from [26] and also given in **Error! Reference source not found.**.

In calculation, the system power loss in terms of load demand and B-matrix coefficients is derived out in [26]. The total costs, emission amount, and equivalent costs obtained from the ALHN method for best CEED are compared to those from AS method [26], MOCPSO [16], and MOCASO [17] in Tables 3, respectively. The Pareto-optimal front obtained by the ALHN for this case is shown in Fig.4. In all cases, the total cost in best economic dispatch, total emission in best emission dispatch, and total equivalent cost in CEED from the proposed method are less than those from the others. For the computational time, the proposed method also obtains solution faster than the others for best economic dispatch and best emission dispatch. Note the computational times obtained in AS, and both MOCPSO and MOCASO are from a Intel Pentium III processor, 996 MHz, 416 MB of RAM PC and a Intel (R) Core (TM) 2 Duo CPU PC with 2.2 GB of RAM, respectively.

Table 2: Comparison of best compromise solution for Case 1b

Load		NR [10]	FCGA [13]	ALHN
500 MW	Fuel cost ($/h)	28,550.15	28,231.06	28,423.7037
	Emission (kg/h)	312.513	304.90	280.3083
	Emission PPF ($/kg)	43.8983	43.8983	43.8983
	Equiv. cost of emission ($/h)	13,718.7894	13,384.5917	12,305.06
	Total equiv. cost ($/h)	42,268.9394	41,615.6517	41,206.8448
700 MW	Fuel cost ($/h)	39,070.74	38,408.82	38,816.1969
	Emission (kg/h)	528.447	527.46	479.8875
	Emission PPF ($/kg)	44.7880	44.7880	44.7880
	Equiv. cost of emission ($/h)	23,668.0842	23,623.8785	21,493.2
	Total equiv. cost ($/h)	62,738.8242	62,032.6985	60,897.5768
900 MW	Fuel cost ($/h)	50,807.24	49,674.28	50,340.0820
	Emission (kg/h)	864.060	850.29	776.2410
	Emission PPF ($/kg)	47.8222	47.8222	47.8222
	Equiv. cost of emission ($/h)	41,321.2501	40,662.7384	37,121.55
	Total equiv. cost ($/h)	92,128.4901	90,337.0184	87,461.63

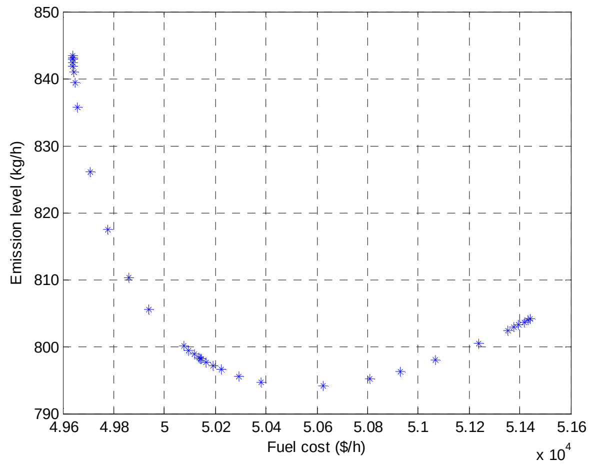

Fig. 3. Pareto-optimal front for fuel cost and emission in Case 1b with load demand of 900 MW

Table 3: Comparison of best compromise solution for Case 2

Method	AS [26]	MOCPSO [16]	MOCASO [17]	ALHN
Fuel cost ($/h)	47,804.55	47,549.87	47,804.59	47,949.78
Emission (kg/h)	843.42	823.36	843.41	735.1226
Emission PPF ($/kg)	47.8222	47.8222	47.8222	47.8222
Equiv. cost of emission ($/h)	40,334.20	39,374.89	40,333.72	35,155.18
Total cost ($/h)	88,138.75	86,924.76	88,138.31	83,104.98

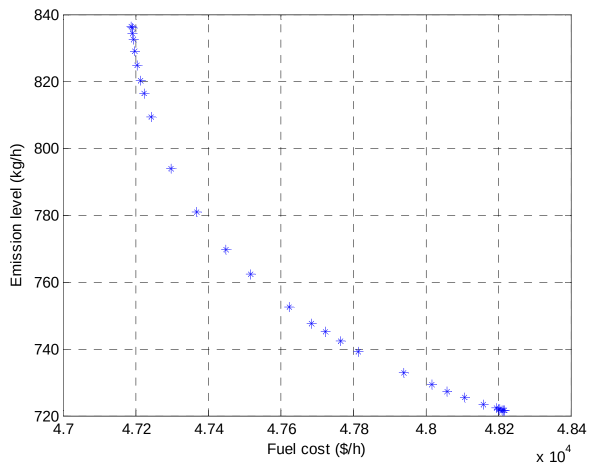

Fig.4. Pareto-optimal front for fuel cost and emission in Case 2

4.3 Case 3: Five-unit system with fuel constraint

The system consists of five thermal units in [19] with fuel constraints supplying to load demand for a 3-week period.

Three sub-cases with differently initial fuel storage are considered for this system. The initial values of fuel storage are given in Table 5.

Table 5: Initial storage for the five-unit system in Case 3

Sub-case	Unit	1	2	3	4	5
1	$X_i^{(0)}$ (tons)	2000	5000	5000	8000	8000
2	$X_i^{(0)}$ (tons)	2000	5000	5000	500	8000
3	$X_i^{(0)}$ (tons)	2000	2500	2500	8000	500

When the system power loss is considered, the obtained results from the ALHN method are given in Table 6 and Pareto-optimal fronts for the sub-cases are shown in Figs.5-7.

Table 6: Results for Case 3 by ALHN

Sub-case		Best compromise
1	Fuel cost ($)	1,034,680.0121
	Emission (kg)	655,494.8034
2	Fuel cost ($)	1,034,673.6641
	Emission (kg)	655,511.7391
3	Fuel cost ($)	1,034,684.4679
	Emission (kg)	655,467.2724

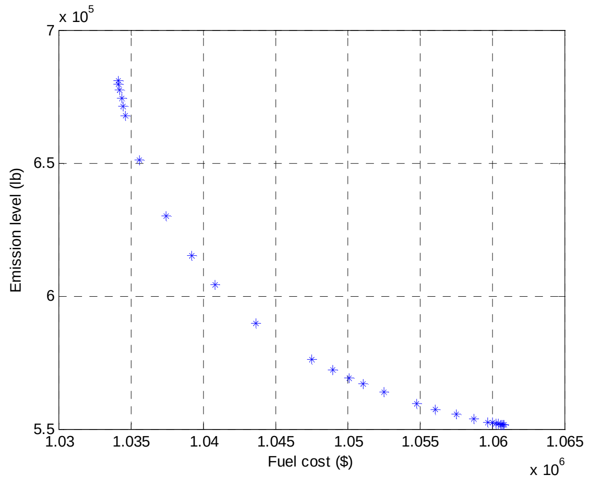

Fig. 5. Pareto-optimal front for fuel cost and emission in Sub-case 1 of Case 3

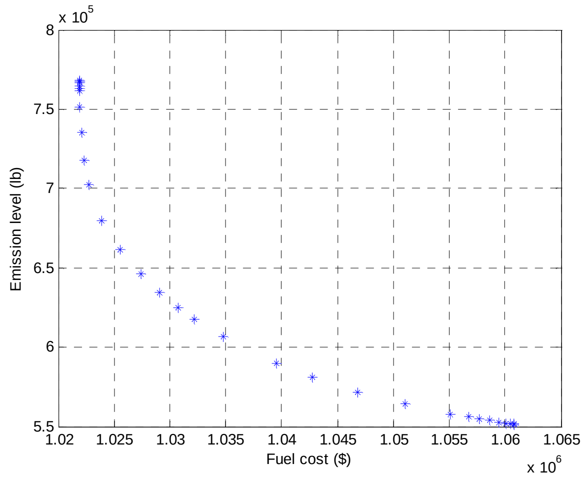

Fig. 6. Pareto-optimal front for fuel cost and emission in Sub-case 2 of Case 3

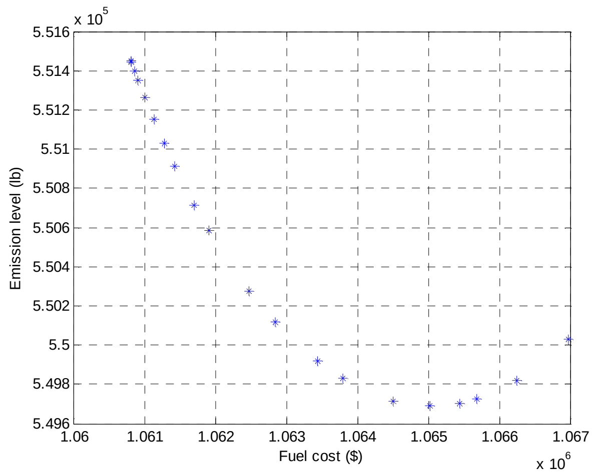

Fig. 7. Pareto-optimal front for fuel cost and emission in Sub-case 3 of Case 3

5. CONCLUSION

In this paper, the ALHN method has been efficiently implemented for solving the CEED problem with fuel constraint. By directly using the augmented Lagrange function as the energy function for Hopfield network together with sigmoid function of continuous neurons, the problem constraints are properly handled. Moreover, ALHN is a recurrent neural network with parallel processing which leads to quick convergence to the optimal solution for the optimization problems. For obtaining different non-dominated solutions of a multi-objective optimization problem, the slope of sigmoid function of continuous neurons is adjusted from very small to very large values. The result comparisons from the many tested cases have shown that the proposed ALHN can obtain better optimal solutions than many other methods. Therefore, ALHN could be a favourable implementation for solving the CEED with complicated constraints.

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Preliminary Problems Identification of Solar Home System Promotion Program in Lao PDR

Bouavone Chanthanileuth, Khamphone Nanthavong, and Zheng Jiliang

Abstract— *National electrification is among the key components in socio-economic development plan of Lao PDR to be removed from the Least Developed Countries list by 2020. In order to achieve the Millennium Development Goal, the Lao government has set up an ambitious target for residential electrification reaching 90% of households by 2020, of which 10% is by an off-grid approach. The Solar Home Systems (SHS) has been considered as the most appropriate solution for off-grid electrification in remote rural areas.*

This paper studied the experiences from the SHS promotion programs in Lao PDR, as well as to study relevant legal documents supporting rural electrification development in Lao PDR.

The research study found that inconsistency in institutional support and policy, inflexibility of delivery mechanism, improper system's standardization and management, inappropriate funding support, probably are among the most important issues in improvement of SHS promotion programs in off-grid areas. Besides, stronger participation of private sector is also a crucial factor for ensuring long term sustainability and reliable service. In this concern, the incentives may not be strong enough for attracting private sector involvement

Keywords— **Solar Home system, private sector involvement, delivery scheme, Off-grid electrification, hire-purchase, rental.**

1. INTRODUCTION

Lao PDR is located in the heart of South East Asia, sharing borders with Cambodia, China, Myanmar, Thailand and Vietnam. The land area is 269,800 km^2 and 70% of which is covered by forest. Of the estimated 6.5 million people in Laos, 85% of that population lives in rural areas. The government of Laos, one of the few remaining one-party communist states, began decentralizing control and encouraging private enterprise in 1986. GDP growth has remained approximately at a steady 7% which is driven by hydropower and mining. The national poverty line has been gradually decreased from 46.1% in 1993 to 26% of population in 2010. Despite this high growth rate, Laos remains a country with an underdeveloped infrastructure, particularly in rural areas. Therefore, national electrification has been considered among the most important issues in socio-economic development programs of Lao Government, to leave least developed countries status.

The government appears committed to raising the country's profile among investors by creating favorable environments for investment in the Lao PDR. The World Bank has declared that Laos' goal of graduating from the UN Development Program's list of least-developed countries by 2020 is achievable.

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2. SITE CONDITIONS

Rural Electrification Policy

In order to achieve development goals, rural electrification has been considered among the most important agendas of development programs of Lao Government. Electric power almost comes entirely from hydro-electric power plants. Electric Power imported from neighboring countries has solely been used for supplying strategic geographical border areas and remains a temporary measure while the national grid is being developed.

Rural electrification programs mainly promote grid connection. However, when grid extension is implemented in more remote rural areas, it becomes less economically viable. In response, the Lao Government has promoted off-grid options for rural electrification, mainly by small scale (micro) hydropower and solar home systems.

The off-grid areas were defined as those, which will not be able to reach grid by the year 2020. The Off-grid areas are typically characterized by difficult access, undeveloped infrastructure (road, communication, electricity and water supply, markets, etc), and rather low population density due to scattered inhabitation.

In order to emphasize the national electrification programs the Lao government has issued, since the late 1990s, several crucial legal documents such as the Electricity Law (1997, revised 2009), Power sector development plan (2001), National Renewable energy development strategy (2011), Rural Electrification Master Plan (2010); being drafted some decrees on small scale hydropower, biofuel, Solar energy, Other Biomass and alternative energy.

Electricity law [2] sets out the regime for the administration, production, transmission and distribution of electricity, including export and import, through the use of productive natural resource potential to contribute to the implementation of the national socio-economic development plan and to upgrade liming standard of the people. The law allows individual or entities to develop hydropower in rural areas with install capacity less than 15 MW and obtaining approvals from relevant local authorities. The law encourages local investors participating in development of this sector.

Power System Development Plan [1] aims to maintain and expand an affordable, reliable and sustainable electricity supply within the country. Therefore, the purpose is to promote economic and social development; promote power generation for export to provide revenues to meet government development objectives; and ensure sustainability by developing and enhancing the legal and regulatory framework to effectively direct and facilitate power sector development; and reforming of institutional structural to clarify responsibilities and streamline administration.

The Renewable Energy Development Strategy [5] focuses on small power development for self sufficiency, grid connection, bio-fuel production and marketing, and development of other clean energies and emphasizes on promoting investment in energy productions from public and private sectors including local and foreign investors. By 2025 the Lao government aims to increase the share of renewable energies to 30% of the total energy consumption.

To reduce the import of fossil fuels, the government outlines a tentative vision to reach 10% of the total transport energy consumption per year from **bio-fuels** by 2025. In Lao PDR hydropower with capacity less than 15 MW is considered as small scale. Lao PDR has a potential for **small hydropower** development around 2,000 MW, of which, 650 MW is to be explored between 2010 and 2025. Lao PDR is located in a zone with relatively good solar irradiance. Solar PV home systems are serving as one of the electrification option in remote rural areas. Current SHS promotion program is aiming for installation of an additional 19,000 households in 331 villages of 11 provinces for the period 2010-2020. Besides that, the government also encourages development of large solar PV farm as an additional supply source for the grid. The government aims to sustain development of household and community scale **biogas** systems using animal and livestock wastes by 50,000 kg in 2025 to reduce the import of liquefied petroleum gas (LPG). Being a predominantly agriculture-based economy, Lao PDR generates substantial amount of wastes from agriculture and forest production and processing such as rice husks, corn cobs and wood wastes. **Biomass** cooking fuels are estimated to represent around 70% of the total energy consumption in Lao PDR. **Wind energy** can be potentially developed for large-scale grid-connection power generation and for hybrid systems providing energy services to rural and remote villages. The government aims to develop around 50 MW of wind power by 2025.

Rural Electrification Master Plan [3] imposes necessary approaches such as planning and monitoring of electrification by data management linked with geographical and visual information; national level standardized criteria of selection process of target villages and its electrification method with rational process using economic evaluation; and effective and sustainable financing plan based on optimum rural electrification plan. Rural electrification approaches are to improve the national electrification ratio from the current 70% to 90% by 2020 (80% by on-grid and 10% by off-grid) and minimize Micro Hydropower (MHP) due to the high cost of operations and maintenance while SHS shall be adopted as a temporary power source for villages in remote areas where grid extension is currently judged to be not feasible. The Off-grid component includes MHP, SHS/BCS, Pico-hydro, diesel generator and hybrid system.

Government Decrees on renewable energy and small hydropower are being drafted. Below is sample of the decrees:

Decree (draft) on solar energy development defines the principle, rules, and measures on the implementation, operation and supervision of solar energy business, to promote solar energy utilization including on-grid and off-grid options for increasing cleaner energy for self consumption and creating economically and technically viable promotion mechanism for solar technology development in Lao PDR.

On the other hand, decree (draft) on biomass gasification defines the principles, rules, and measures on the implementation, operation, regulation and supervision of biomass gasification business, to promote biomass-based power generation development including on-grid and off-grid options and to develop domestic small and medium size biomass gasification digester, for increasing cleaner energy for self consumption, effective agro-forestry-livestock wastes treatment aiming at creating economically and technically viable promotion mechanism for biomass technology in Lao PDR.

And finally, the decree (draft) on biogas production defines the principles, rules, and measures on the implementation, operation, regulation and supervision of biogas business, to promote biogas energy production including on-grid and off-grid options and to develop domestic small and medium size biogas digester, for increasing cleaning energy for self consumption, effective agro-forestry-livestock wastes treatment aiming at creating economically and technically viable promotion mechanism for biogas technology in Lao PDR.

Rural Electrification Status

Connection Ratio: The national mean connection ratio to the grid is about 80%. In case of off-grid SHS, the introduction ratio is said to be approximately 60%. Considering that present grid connection ratio would remain at 80% as well as the off-grid introduction ratio at 60%, the government could still not achieve the target electrification rate of 80% by grid and 10% by off-grid, even if all villages in the Lao PDR are covered by grid and off-grid electrification. Hence, it is requested to improve the connection ratio in electrified villages together with rural electrification implementation. The Power to the Poor (P2P) project under Rural

Electrification Plan (REP-1) has a record in improving the connection ratio from 81% up to 94% in the pilot project conducted in 2008. Expansion of P2P project to improve the national average connection ratio up to the level of 95% or more is necessary to achieve the electrification goal. As shown in Table1-1, 1-2 and Figure 1, in 2010 national electrification ratio throughout the country.

Off-Grid Options: Grid extension to remote areas of the country is economically not viable due to difficult mountainous landscape, plus sparse population density, low power demand, undeveloped infrastructure Therefore, Government turned to promote off-grid options rural electrification, which may included stand along PV Systems, small scale, hydropower, charging station, etc.

Table 1. Electricity Statistics

Year	Total amount		
	Districts	Villages	HH
1998	141	11,456	754,265
1999	141	11,058	768,142
2000	142	11,263	818,668
2001	142	11,231	866,277
2002	142	11,168	875,774
2003	142	10,866	883,355
2004	141	10,781	930,982
2005	139	10,473	1,000,350
2006	140	10,583	943,810
2007	140	9,630	959,094
2008	141	9,528	972,419
2009	141	9,063	1,026,012
2010	143	8,918	1,034,623

Table 2. Electricity Statistics

Year	**Electrified in 2010**					
	Districts	%	Villages	%	HH	%
1998	102	72	1,884	16	226,004	30
1999	109	77	2,507	23	254,610	33
2000	119	84	2,651	24	293,494	36
2001	116	82	2,811	25	303,690	35
2002	125	88	3,245	29	340,550	39
2003	128	90	3,776	35	379,109	43
2004	127	90	4,229	39	437,649	47
2005	132	95	4,510	43	483,133	48
2006	132	94	5,294	50	510,529	54
2007	136	97	4,940	51	566,110	59
2008	136	96	5,010	54	608,796	63
2009	137	97	5,811	64	714,613	70
2010	137	96	5,686	64	738,065	71

Source: Electricity Statistics Years Book 2010 of Lao PDR [4]

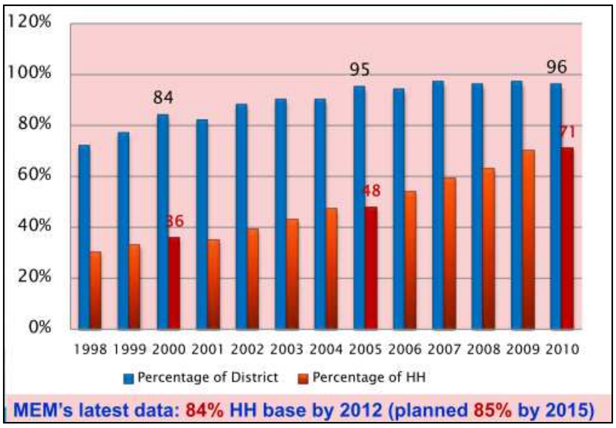

Fig. 1. Rural Electrification Status

Small scale Hydropower

Advantages*:* Hydropower electricity is generated from environmental friendly renewable natural resources, which help avoiding importing fossil oil products and hence, contribute to CO_2 emission reduction. Good for household and industrial use

Disadvantages*:* As a rule, SHP represents higher specific initial investment costs, comparing to larger HP. SHP strongly depends on local conditions, seasonal resource changes. Therefore, Energy generation highly depends on varying resource availability. Besides, Local communities lack of capacity to operate and maintain the system themselves.

Solar Home System/SHS

SHS is the main source in off-grid rural electrification while promotion of MHP is limited which due the high cost of investment and O&M difficulties. The promotion of SHS has become the most appropriate measure in power supply for villages in remote areas, where grid extension is currently judged to be not feasible.

Advantages*:* Relatively good solar irradiance (4-5 $KWh/m^2/day$), plus well known factors such as easy installation, low maintenance costs, long life equipment, as well as less environmental impacts remote rural villagers, while waiting for grid connection.

The Disadvantages of SHS are rather high equipment cost, short life of battery pack, limited power supply. In order to achieve reliable energy supply it will need to be combined with other energy sources and therefore, be a more costly solution.

Solar Battery Charging Station (SBCS)

This is a collective use system; the users have to pay for a rechargeable battery, limited appliance (mainly light) and a charging fee.

Advantages*:* This is a lesser cost option for rural people: users have ability to manage their energy usage and payment according to actually used energy only.

.**Disadvantage*:*** The common problems for SBCS are improper management approach that often leads to system failures. The environmental concern would be a disposal of numerous unused batteries.

Diesel Generator

Advantage: Perhaps this is the lowest initial investment option and can be a temporary solution until grid connection.

Disadvantages: High operation cost due to unstable fuel price and high fuel delivery costs to difficult-to-access remote areas, as well as environmental concerns of CO_2 emission.

Hybrid Systems

There are two hybrid systems which have been piloted in Lao PDR by NEDO[1] 1) SHP+PV in Oudomxay province and 2) SHP+PV+Capacitor in Phongsaly province [MEM-NEDO project].

Advantages*:* More reliable power supply and use of clean local resources as much as possible.

Disadvantages*:* High system costs.

Overal observation on off-grid Rural electrification programs in Lao PDR:

- Almost all micro hydropower installations (around 40 sites with capacity less than 100 MW) completely failed.
- SBCS could not find sustainable application, as well as diesel generator approach.
- SHS promotion can be considered as the most successful off-grid electricity installation option in Lao PDR.

Solar Home Promotion Programs in Laos PDR

The SHS program was initiated under the Southern Provinces Rural Electrification Project (1998-2004) and originally implemented by Electricite Du Laos (EDL). In February 2001, the responsibility of SHS program was then transferred to Ministry of Energy and Mines (MEM). The Off-Grid Promotion Support Office (OPS) was established within the Department of Electricity of MEM. In March 2001, MEM's Power Sector Policy Statement established the policy and regulatory mandate for Provincial Energy Service Companies (PESCOs) as intermediary entities to plan, help organize and install and then provide ongoing support to off-grid schemes in rural areas of the Lao PDR.

Up to 2010, totally 16,247 SHS of capacity between 20-50 Wp have been installed in 16 provinces (447 villages) of Lao PDR by various programs such as TRI's solar PV demonstration projects (1997-2001) under Technology Research Institute; MEM-JICA solar PV pilot projects (1998-2001) and MEM-WB Hire-purchase projects (1999-2004) owned by the Ministry of Energy and Mine; and Sunlabob-InWent pilot projects on Rental PV systems (since 2003) invested by private investor [8].

Currently four delivery models of stand-alone SHS have been carried out in the country: donation, cash sales, rental system and hire-purchase.

- **Rental system** is carried by Sanlabob co., which established in 2001. The company rents the hardware (equipment) to villagers and collects the fee.

  Management mechanism: In additional situation, if systems work properly, users pay monthly rent. The Village Electricity Committee (VEC) is able to transfer tariffs to the rental company and then receive margins. The rental company receives money to pay for the loan plus interest and receives income.

  Advantages: Users pay for used electricity only, equipment remains property of Rental Company. Service reliability is ensured by an established franchise with high quality equipment installed to ensure sustainability. The systems are installed and maintained by the hardware company's skilled technicians. On the other hand, the Energy Service Company (ESCO) has strong incentive to keep the system in good working conditions. And the flexibility of this system is such that the users are not required to do maintenance work or spare part replacement; this makes it an affordable choice.

  ***Disadvantages*:** High rental cost. In order to reduce service costs in remote rural areas, the rental company may install high quality and reliable equipment, installation by company qualified technicians, and therefore, rental costs will be rather high, and unaffordable for majority of rural people.

- **MEM-WB Hire-purchased model**: villagers choose a range of solar PV panel sizes, then lease the system and make the payment over a certain period (5 or 10 years) and after that the system becomes their property. Installation and maintenance of the system are carried by village energy manager (VEM), who got trained by the project counterparts and service is undertaken ESCO, which was set up by the project [9].

  Management mechanism: If system work properly, users pay monthly payment and then village energy manager (VEM) can make repayment to ESCO and get operational rebates. Therefore, ESCO is able to transfer money to OPS and can receive operational rebates.

  Advantages: the users own the equipment after repayment period is complete. Lower repayment rate is due to subsidy by the project. Well-designed financial incentives for planning, delivery, training and operational rebates and prospective ownership are available due to Soft Loan support.

  Disadvantages: Based on the information, the users pay for spare parts and installation fee and the available service is unreliable. The low profit business is unattractive for businesses and entrepreneurs. There are at times improper installation and servicing by unskilled technicians. And lastly, low quality equipment usually installed

[1] **NEDO:** New Energy and Industrial Technology Development Organization

to avoid high repayment for the system costs.

Lesson learned from SHS programs in Lao PDR

This paper emphasizes how to optimize SHS program management in Lao PDR to provide reliable and sustainable electricity supply by using costly technologies with affordable pricing for villagers with limited financial resources in isolate rural areas. Further studies on the application of an appropriate approach, tools and consistent support mechanisms from funding agencies or relevant organizations to encourage involvement from private initiatives into the business needs to be observed.

- ***TRI's solar PV demonstration projects (BCS and SH-BCS)***

  BCS: Villagers are responsible for the maintenance and replacement of their equipment. The collected fees are used for systems maintenance, spare parts replacement and to pay village technician salary. One key-house manager is required.
  SH-BCS: User's convenience is closer to house users, flexible charging process, lower capital cost. Complex management scheme: deal with many key-house managers. It is difficult to keep service standard as high as for all systems.
  It was observed that detailed management and cost recovery scheme was not worked out; lack of follow up activities and monitoring capacity; lack of management skills and funding support. As result, almost all of installed systems failed or have been evacuated due to grid connection.

- ***MEM-JICA solar PV pilot projects (SHS and BCS)***

  The project has shown that people in rural areas accepted the PV systems and demand is high; Initial payment and monthly fees are affordable for villagers; the setting reasonable market prices is necessary to promote the system; VEC plays a vital role in system management. Qualified VEC is very important; people's participation, capacity building and cost recovery are main points to sustainable operation; Standard system configuration, selecting system part and replacement of parts are main components to be addressed; Competency and incentive of local office of MEM to cope with system's monitoring and support for long term repayment period (15-20 years); Good for users who prefer low repayment, but, the projects need full long-term subsidies in the form of grants, which is not always available.

- ***MEM-WB hire-purchase projects (SHS, VH and GS)***

  For SHS [10], users purchase the equipment and are motivated to maintain its condition. The VEM and ESCO receive a portion of each user's monthly payment called "***operational rebates***", only if the users' payment is actually made. It is a strong incentive for VEM and ESCO to maintain the systems functionality properly in order to get the rebates. OPS does not approve plans for installation in new villages, if the ESCO is not matching an average repayment rate of above 95% from its entitled villages. Poor service of ESCO will skip its business.

- ***Sunlabob-InWent's pilot projects on Renting PV systems***

  The project was launched in cooperation between Sunlabob Co., LTD and InWent-Capacity building International (Germany), with consulting support by Viltec (Switzerland). The project was to prove that the rental mechanism within selective areas such as those along the national road, national borderlines and densely populated areas, where people normally have relatively high income and many belong to future grid expansion. The project involves many parties: government authorities, funding agency, rental company (hardware company), training company and village committee (VEC). The delivery model economically is not suitable for major rural population in remote areas due to high rental fee.

3. DISCUSSIONS

The issue reviewed in site conditions section of the right delivery model is the most critical. Cash sales model appears the least likely to succeed because the target areas for SHS installation will be in isolated areas or highlands where poverty is most pronounced. Donation (donated system) is possible, depending on donors' level of support and duration. Rental scheme may have reliable franchise network and a tendency of installing high quality equipment, but rental fee is high, not affordable for the poor. Hire-purchase scheme receives good financial support that makes systems price affordable for the poor in RE, but the scheme may face challenges of systems and service reliability, especially when demanding increased.

Technical Challenges

- Replace lead acid battery & light every 2-3 years,
- Too expensive for deep cycle lead acid battery,
- It is low quality of panels and short lifespan than the payment scheme,
- There is no supply chain,
- No recommendable component, which available in general market,
- Spare parts replacement is very costly,
- Poor system installation and maintenance by unskilled technicians.

Domestic Challenges

- There is no comprehensive SHS strategy.
- Projects are carried out independently without integrated national electrification plan.
- Target villages are selected extemporary based on local information.

- SHS promotion has not yet been clearly stated in the NSEDP or in Growth and Poverty Reduction Strategy or in 5-year Plan.
- Insufficient information and handbook supplied to users.
- Lack of public funding. Rural Electrification Fund (REF) now uses the fund for the purchase of the spare parts, mainly batteries.
- Lack of private incentive for investment.
- Sell livestock to cover the monthly fee in remote areas.
- Prefer grid electricity rather than off-grid one.

The Policy of SHS Program

- Solar Home Systems installation is one of the viable options for the off-grid component of rural electrification programs, and has been promoted by either national or international organizations.
- Consistent institutional and financial support, appropriate incentive measures, involvement of private sector, etc, are other important factors for success of the SHS programs.
- By observing the implemented pilot programs for SHS, government subsidy on hire- purchase scheme is considered the best practice or model for rural population in Laos.

Servicing and Customized Solutions

- The most interesting delivery models for SHS in Lao PDR include hire-purchase scheme, offered by rural electrification division (MEM) with Soft Loan support by the World Bank and Rental system – a pure commercial initiative offered by Sanlabob Rural Electrification Co.
- Currently lead acid in automotive batteries is used due to cheap and availability in general market. If replacing the lead acid one with deep cycle lead acid battery, the system would be working properly. However, this may be too expensive for those with limited financial resources.
- If the government can subsidize the cost of ordinary battery replacement and let users pay for the installation fee or fixing fee. The issue might be solved.
- If a proper supply chain is set up to control quality of spare parts, long SHS lifespan would last longer.
- Also, if technical staff is well trained to O&M the system closely, system failure rate might be reduced.

Local Supplies and Domestic Challenges

- If a data centre is set up to gather all relevant information related to SHS project implementations in Laos regarding number of systems actually installed and operating SHS plus any plan for expansion, this would help in assessing the project's output and impose necessary measures to manage the system in the long run.
- If the government is able to negotiate with the existing or new donors to obtain aid on SHS promotions in Laos, financial constrain might be no longer an issue.
- If an independent institution is set up to look after all government related projects directly in Laos, the issues on lack of co-operations between relevant institutions and management overlaps might be reduced.
- If campaign on SHS promotions is broadcasted nationwide, it may help to stimulate users' incentives and participations.

4. CONCLUSIONS

After identifying the situation, analysis, and studying a variety of SHS programs operating in Lao PDR, the following practices have been concluded:

- The well integrated government policy is crucial. The present policy on renewable energy only marginally touches on the SHS aspect, which is surprising considering that the market represents a success story out at the rural area.
- Long term system sustainability of SHS promotion program in Lao PDR depends on such factors system standards and quality, flexibility in spare parts supply, proper installation.
- Establishment of data centre is essential, in order to share experiences and lessons learned from failed and succeeded projects
- Workable institutional mechanism and good coordination among the relevant organizations are important factors for ensuring long-term sustainability in off-grid rural electrification programs and furthermore, to avoid overlapping either in term of promoted technology or funding support.
- Financial support to start-up capital or revolving fund for ESCOs can help attracting more involvement of private sector investment. In this meaning, soft loans to ESCOs by Rural Electrification Fund are essential.
- In other hand, the issues such as inconsistency in institutional support and policy inflexibility of delivery mechanism, improper system's standardization and management, inappropriate funding support probably are among the most important issues that need to be addressed in order to improve SHS promotion programs in off-grid areas.
- And, the members of the community can serve as salespeople and technicians if they receive proper training. The local supporters will understand the community and relate to the customers better than any outsiders.

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Particle Swarm Optimization with Constriction Factor for Optimal Reactive Power Dispatch

Vo Ngoc Dieu, Le Anh Dung, and Nguyen Phuc Khai

Abstract— *This paper proposes a simple particle swarm optimization with constriction factor (PSO-CF) method for solving optimal reactive power dispatch (ORPD) problem. The proposed PSO-CF is the conventional particle swarm optimization based on constriction factor which can deal with different objectives of the problem such as minimizing the real power losses, improving the voltage profile, and enhancing the voltage stability and properly handle various constraints for reactive power limits of generators and switchable capacitor banks, bus voltage limits, tap changer limits for transformers, and transmission line limits. The proposed method has been tested on the IEEE 30-bus and IEEE 118-bus systems and the obtained results are compared to those from other PSO variants and other methods in the literature. The result comparison has shown that the proposed method can obtain total power loss, voltage deviation or voltage stability index less than the others for the considered cases. Therefore, the proposed PSO-CF can be favorable solving the ORPD problem.*

Keywords— **Constriction factor, optimal reactive power dispatch, particle swarm optimization, voltage deviation, voltage stability index.**

NOMENCLATURE

G_{ij}, B_{ij}	Transfer conductance and susceptance between bus *i* and bus *j*, respectively
g_l	Conductance of branch *l* connecting between buses *i* and *j*
L_i	Voltage stability index at load bus *i*
N_b	Number of buses
N_d	Number of load buses
N_g	Number of generating units
N_l	Number of transmission lines
N_t	Number of transformer with tap changing
P_{di}, Q_{di}	Real and reactive load demand at bus *i*, respectively
P_{gi}, Q_{gi}	Real and reactive power outputs of generating unit *i*, respectively
Q_{ci}	Reactive power compensator at bus *i*
S_l	Apparent power flow in transmission line *l* connecting between bus *i* and bus *j*
T_k	Tap-setting of transformer branch *k*
V_{gi}	Voltage at generation bus *i*
V_{gi}, V_{li}	Voltage magnitude at generation bus *i* and load bus *i*, respectively
V_i, δ_i	Voltage magnitude and angle at bus *i*, respectively

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1. INTRODUCTION

Optimal reactive power dispatch (ORPD) is to determine the control variables such as generator voltage magnitudes, switchable VAR compensators, and transformer tap setting so that the objective function of the problem is minimized while satisfying the unit and system constraints [1]. In the ORPD problem, the objective can be total power loss, voltage deviation at load buses for voltage profile improvement [2], or voltage stability index for voltage stability enhancement [3]. ORPD is a complex and large-scale optimization problem with nonlinear objective and constraints. In power system operation, the major role of ORPD is to maintain the load bus voltages within their limits for providing high quality of services to consumers.

The problem has been solved by various techniques ranging from conventional methods to artificial intelligence based methods. Several conventional methods have been applied for solving the problem such as linear programming (LP) [4], mixed integer programming (MIP) [5], interior point method (IPM) [6], dynamic programming (DP) [7], and quadratic programming (QP) [8]. These methods are based on successive linearizations and use gradient as search directions. The conventional optimization methods can properly deal with the optimization problems of deterministic quadratic objective function and differential constraints. However, they can be trapped in local minima of the ORPD problem with multiple minima [9]. Recently, meta-heuristic search methods have become popular for solving the ORPD problem due to their advantages of simple implementation and ability to find near optimum solution for complex optimization problems. Various meta-heuristic methods have been applied for solving the problem such as evolutionary programming (EP) [9], genetic algorithm (GA) [3], ant colony optimization algorithm (ACOA) [10], differential evolution (DE) [11], harmony search (HS) [12], etc. These methods can improve optimal solutions for the ORPD problem compared to the conventional methods but with relatively slow performance. Among the meta-heuristic search methods, particle swarm optimization (PSO) is the most popular one for solving the ORPD problem including many variants such as multiagent-based PSO [13], enhanced PSO [2], parallel PSO [14], comprehensive learning PSO [15], etc. The PSO methods are generally simpler implementation, more powerful search ability, and faster performance than other meta-heuristic search methods, leading to solution quality for optimization problems considerably improved. In addition the single methods, hybrid methods have been also widely implemented for solving the problem such as hybrid GA [16], hybrid EP [17], hybrid PSO [18], etc to utilize the advantages of the single methods. The hybrid methods usually obtain better solution quality than the single methods but they also suffer longer computational time.

In this paper, a simple particle swarm optimization with constriction factor (PSO-CF) method is proposed for solving the ORPD problem. The proposed PSO-CF is the particle swarm optimization based on constriction factor which can deal with different objectives of the problem such as minimizing the real power losses, improving the voltage profile, and enhancing the voltage stability and properly handle various constraints for reactive power limits of generators and switchable capacitor banks, bus voltage limits, tap changer limits for transformers, and transmission line limits. The proposed method has been tested on the IEEE 30-bus and IEEE 118-bus systems and the obtained results are compared to those from other PSO variants and other methods in the literature.

The remaining organization of this paper is follows. Section 2 addresses the formulation of ORPD problem. A PSO-CF implementation for the problem is described in Section 3. Numerical results are presented in Section 4. Finally, the conclusion is given.

2. PROBLEM FORMULATION

The objective of the ORPD problem is to minimize is to optimize the objective functions while satisfying several equality and inequality constraints. Mathematically, the problem is formulated as follows:

$$\text{Min } F(x,u) \tag{1}$$

where the objective function *F(x,u)* can be expressed in one of the forms as follows:

- Real power loss:

$$F(x,u) = P_{loss} = \sum_{i=1}^{N_l} g_l \left[V_i^2 + V_j^2 - 2V_iV_j \cos(\delta_i - \delta_j) \right] \tag{2}$$

- Voltage deviation at load buses for voltage profile improvement [2]:

$$F(x,u) = VD = \sum_{i=1}^{N_d} \left| V_i - V_i^{sp} \right| \tag{3}$$

where V_i^{sp} is the pre-specified reference value at load bus *i*, which is usually set to 1.0 pu.

- Voltage stability index for voltage stability enhancement [3], [19]:

$$F(x,u) = L_{\max} = \max\{L_i\};\ i = 1,...,N_d \tag{4}$$

For all the considered objective functions, the vector of dependent variables *x* represented by:

$$x = [Q_{g1},..., Q_{gN_g}, V_{l1},..., V_{lN_d}, S_1,..., S_{N_l}]^T \tag{5}$$

and the vector of control variables *u* represented by:

$$u = [V_{g1},..., V_{gN_g}, T_1,..., T_{N_t}, Q_{c1},..., Q_{cN_c}]^T \tag{6}$$

The problem includes the equality and inequality constraints as follows:

a) Real and reactive power flow equations at each bus:

$$P_{gi} - P_{di} = V_i \sum_{j=1}^{N_b} V_j \left[G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j) \right] \quad i = 1,..., N_b \tag{7}$$

$$Q_{gi} - Q_{di} = V_i \sum_{j=1}^{N_b} V_j \left[G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j) \right] \quad i = 1,..., N_b \tag{8}$$

b) Voltage and reactive power limits at generation buses:

$$V_{gi,\min} \le V_{gi} \le V_{gi,\max};\ i = 1,..., N_g \tag{9}$$

$$Q_{gi,\min} \le Q_{gi} \le Q_{gi,\max};\ i = 1,..., N_g \tag{10}$$

c) Capacity limits for switchable shunt capacitor banks:

$$Q_{ci,\min} \le Q_{ci} \le Q_{ci,\max};\ i = 1,..., N_c \tag{11}$$

d) Transformer tap settings constraint:

$$T_{k,\min} \le T_k \le T_{k,\max};\ k = 1,..., N_t \tag{12}$$

e) Security constraints for voltages at load buses and transmission lines:

$$V_{li,\min} \le V_{li} \le V_{li,\max};\ i = 1,..., N_d \tag{13}$$

$$S_l \le S_{l,\max};\ l = 1,..., N_l \tag{14}$$

where the S_l is the maximum power flow between bus *i* and bus *j* determined as follows:

$$S_l = \max\{|S_{ij}|, |S_{ji}|\} \quad (15)$$

3. PARTICLE SWARM OPTIMIZATION WITH CONSTRICTION FACTOR

3.1 Basic particle swarm optimization

PSO is a population based evolutionary computation technique inspired from the social behaviors of bird flocking or fish schooling. Since the first invention in 1995 [20], PSO has become one of the most popular methods applied in various optimization problems due to its simplicity and ability to find near optimal solutions. In the conventional PSO, a population of particles moves in the search space of problem to approach to the global optima. The movement of each particle in the population is determined via its location and velocity. During the movement, the velocity of particles is changed over time and their position will be updated accordingly. For implementation in a n-dimension optimization problem, the position and velocity vectors of particle *d* are represented by $x_d = [x_{1d}, x_{2d}, \ldots, x_{nd}]$ and $v_d = [v_{1d}, v_{2d}, \ldots, v_{nd}]$, respectively, where $d = 1,\ldots, NP$ and NP is the number of particles. The best previous position of particle *d* is based on the valuation of fitness function represented by $pbest_d = [p_{1d}, p_{2d}, \ldots, p_{nd}]$ and the best particle among all particles represented by *gbest*. The velocity and position of each particle in the next iteration (k+1) for fitness function evaluation are calculated as follows:

$$v_{id}^{(k+1)} = w^{(k+1)} \times v_{id}^{(k)} + c_1 \times rand_1 \times \left(pbest_{id}^{(k)} - x_{id}^{(k)} \right) + c_1 \times rand_2 \times \left(gbest_i^{(k)} - x_{id}^{(k)} \right) \quad (16)$$

$$x_{id}^{(k+1)} = x_{id}^{(k)} + v_{id}^{(k+1)} \quad (17)$$

where the constants c_1 and c_2 are cognitive and social parameters, respectively and $rand_1$ and $rand_2$ are random values in [0, 1].

3.2 Implementation of constriction factor

The position and velocity for each particle have their own limits. For the position limits, the lower and upper bounds are from the limits of variables represented by the particle's position. However, the velocity limits for the particles can be defined by users. Generally, the solution quality of the PSO method for optimization problems is sensitive to the cognitive and social parameters and velocity limit of particles. Therefore, there have been several attempts to control the exploration and exploitation abilities of the PSO algorithm by adjusting the cognitive and social factors or to limit the range of velocity in the range [$-v_{id,max}$, $v_{id,max}$]. In this paper, the improved PSO with constriction factor proposed in [21] is implemented for solving the ORPD problem. The authors have claimed that the use of a constriction factor may be necessary to insure the stable convergence of the PSO algorithm. The modified velocity for the particles with constriction factor is expressed as follows:

$$v_{id}^{(k+1)} = C \times \left[v_{id}^{(k)} + c_1 \times rand_1 \times \left(pbest_{id}^{(k)} - x_{id}^{(k)} \right) + c_2 \times rand_2 \times \left(gbest_i^{(k)} - x_{id}^{(k)} \right) \right] \quad (18)$$

$$C = \frac{2}{\left| 2 - \varphi - \sqrt{\varphi^2 - 4\varphi} \right|}; \text{ where } \varphi = c_1 + c_2,\ \varphi > 4 \quad (19)$$

In the PSO-CF, the factor φ has an effect on the convergence characteristic of the system and must be greater than 4.0 to guarantee stability. However, as the value of φ increases, the constriction C decreases producing diversification which leads to slower response. The typical value of φ is 4.1 (i.e. $c_1 = c_2 = 2.05$) as proposed in [22]. When the constriction factor implemented in the PSO, the search procedure ensures the convergence for the method based on the mathematical theory. Consequently, the PSO-CF can obtain better quality solutions than the basic PSO approach.

3.3 PSO-CF for the ORPD problem

For implementation of the proposed PSO-CF to the problem, each particle position representing for control variables is defined as follows:

$$x_d = [V_{g1d}, \ldots, V_{gN_gd}, T_{1d}, \ldots, T_{N_td}, Q_{c1d}, \ldots, Q_{cN_cd}]^T \quad d = 1, \ldots, NP \quad (20)$$

The upper and lower limits for velocity of each particle are determined based on their lower and upper bounds of position:

$$v_{d,\max} = R \times (x_{d,\max} - x_{d,\min}) \quad (21)$$

$$v_{d,\min} = -v_{d,\max} \quad (22)$$

where R is the limit factor for particle velocity.

Both particle positions and velocities are initialized within their limits given by:

$$x_d^{(0)} = x_{d,\min} + rand_3 \times (x_{d,\max} - x_{d,\min}) \quad (23)$$

$$v_d^{(0)} = v_{d,\min} + rand_4 \times (v_{d,\max} - v_{d,\min}) \quad (24)$$

where $rand_3$ and $rand_4$ are random values in [0, 1].

During the iterative process, the positions and velocities of particles are always adjusted in their limits after being calculated in each iteration as follows:

$$v_d^{new} = \min\{v_{d,\max}, \max\{v_{d,\min}, v_d\}\} \quad (25)$$

$$x_d^{new} = \min\{x_{d,\max}, \max\{x_{d,\min}, x_d\}\} \quad (26)$$

The fitness function to be minimized is based on the problem objective function and dependent variables including reactive power generations, load bus voltages, and power flow in transmission lines. The fitness function is defined as follows:

$$FT = F(u,x) + K_q \sum_{i=1}^{N_g} \left(Q_{gi} - Q_{gi}^{\lim}\right)^2 + K_v \sum_{i=1}^{N_d} \left(V_{li} - V_{li}^{\lim}\right)^2 + K_s \sum_{l=1}^{N_l} \left(S_l - S_{l,\max}\right)^2 \quad (27)$$

where K_q, K_v, and K_s are penalty factors for reactive power generations, load bus voltages, and power flow in transmission lines, respectively.

The limits of the dependent variables in (25) are determined based on their calculated values as follows:

$$x^{\lim} = \begin{cases} x_{\max} & if\ x > x_{\max} \\ x_{\min} & f\ x < x_{\min} \end{cases} \quad (28)$$

whrere x and x^{lim} respectively represent for the calculated value and limits of Q_{gi}, V_{li}, or $S_{l,max}$.

The overall procedure of the proposed PSO-CF for solving the ORPD problem is addressed as follows:

Step 1: Choose the controlling parameters for PSO-CF including number of particle *NP*, maximum number of iterations IT_{max}, cognitive and social acceleration factors c_1 and c_2, limit factor for maximum velocity *R*, and penalty factors for constraints.

Step 2: Generate *NP* particles for control variables in their limits including initial particle position x_{id} representing vector of control variables in (5) and velocity v_{id} as in (23) and (24), where $i = 1, …, N_g + N_t + N_c$ and $d = 1, …, NP$.

Step 3: For each particle, calculate value of dependent variables based on power flow solution using Matpower toolbox and evaluate the fitness function F_{pbestd} in (27). Determine the global best value of fitness function $F_{gbest} = \min(F_{pbestd})$.

Step 4: Set $pbest_{id}$ to x_{id} for each particle and $gbest_i$ to the position of the particle corresponding to F_{pbestd}. Set iteration counter $k = 1$.

Step 5: Calculate new velocity $v^{(k)}_{id}$ and update position $x^{(k)}_{id}$ for each particle using (18) and (17), respectively. Note that the obtained position and velocity of particles should be limited in their lower and upper bounds given by (25) and (26).

Step 6: Solve power flow using Matpower toolbox based on the newly obtained value of position for each particle.

Step 7: Evaluate fitness function FT_d in (27) for each particle with the newly obtained position. Compare the calculated FT_d to $F^{(k-1)}_{pbestd}$ to obtain the best fitness function up to the current iteration $F^{(k)}_{pbestd}$.

Step 8: Pick up the position $pbest^{(k)}_{id}$ corresponding to $F^{(k)}_{pbestd}$ for each particle and determine the new global best fitness function $F^{(k)}_{pbestd}$ and the corresponding position $gbest^{(k)}_i$.

Step 9: If $k < IT_{max}$, $k = k + 1$ and return to Step 5. Otherwise, stop.

4. NUMERICAL RESULTS

The proposed PSO-CF has been tested on the IEEE 30-bus and 118-bus systems with different objectives including power loss, voltage deviation, and voltage stability index. The data for these systems can be found in [23], [24]. The characteristics and the data for the base case of the test systems are given in Tables 1 and 2, respectively.

In this paper, the power flow solutions for the systems are obtained from Matpower toolbox [24]. For comparison, three other variants of PSO also implemented for solving the problem are PSO with time-varying inertia weight (PSO-TVIW) [25] and PSO with time-varying acceleration coefficients (PSO-TVAC) and self organizing hierarchical particle swarm optimizer with time-varying acceleration coefficients (HPSO-TVAC) in [26]. The algorithms of the PSO methods are coded in Matlab platform [27] and run on a 2.1 GHz with 2 GB of RAM PC. The parameters of the PSO methods for the test systems are given in Table 3. For stopping criteria, the maximum number of iterations for all PSO methods is set 200. For each test case, the PSO methods are performed 50 independent runs.

4.1 IEEE 30-bus system

In the test system, the generators are located at buses 1, 2, 5, 8, 11, and 13 and the available transformers are located on lines 6-9, 6-10, 4-12, and 27-28. The switchable capacitor banks will be installed at buses 10, 12, 15, 17, 20, 21, 23, 24, and 29 with the minimum and maximum values of 0 and 5 MVAR, respectively. The limits for control variables are given in [11], generation reactive power in [28], and power flow in transmission lines in [29]. The number of particles for the PSO methods in this case is set to 10.

The results obtained by the PSO methods for the system with different objectives including power loss, voltage deviation for voltage profile improvement, and voltage stability index for voltage enhancement are given in Tables 4, 5, and 6, respectively and the solutions for best results are given in Tables A1, A2, and A3 of Appendix.

The obtained best results from the proposed PSO-CF method are compared to those from DE [11], comprehensive learning particle swarm optimization (CLPSO) [15], and other PSO variants for different objectives as given in Table 7. For the objective of total power loss and voltage deviation, the optimal solutions by the proposed PSO-CF are less than those from the others while the best voltage stability index from the PSO-CF method is approximate to that from others and better than that of HPSO-TVAC. For computational time, the CLPSO method obtained its optimal solution for an average of 138 seconds which is vastly slower than that from the PSO-CF method. There is no report of computational time for the DE method.

Table 1. Characteristics of test systems

System	No. of branches	No. of generation buses	No. of transformers	No. of capacitor banks	No. of control variables
IEEE 30 bus	41	6	4	9	19
IEEE 118 bus	186	54	9	14	77

Table 2. Base case for test systems

System	ΣP_{di}	ΣQ_{di}	P_{loss}	Q_{loss}	ΣP_{gi}	ΣQ_{gi}
IEEE 30 bus	283.4	126.2	5.273	23.14	288.67	89.09
IEEE 118 bus	4242	1438	132.863	783.79	4374.86	795.68

Table 3. Parameters for PSO methods

Method	PSO-TVIW	PSO-TVAC	HPSO-TVAC	PSO-CF
w_{max}	0.9	-	-	-
w_{min}	0.4	-	-	-
c_1, c_2	2	-	-	2.05
c_{1i}, c_{2f}	-	2.5	2.5	-
c_{1f}, c_{2i}	-	0.2	0.2	-
R	0.15	0.15	0.15	0.15

Table 4. Results by PSO methods for the IEEE 30-bus system with power loss objective

Method	PSO-TVIW	PSO-TVAC	HPSO-TVAC	PSO-CF
Min P_{loss} (MW)	4.5129	4.5356	4.5283	4.5128
Avg. P_{loss} (MW)	4.5742	4.5912	4.5581	4.6313
Max P_{loss} (MW)	5.8204	4.9439	4.6112	5.7633
Std. dev. P_{loss} (MW)	0.1907	0.0592	0.0188	0.2678
VD	2.0540	1.9854	1.9315	2.0567
L_{max}	0.1255	0.1257	0.1269	0.1254
Avg. CPU time (s)	10.98	10.85	10.38	10.65

Table 5. Results by PSO methods for the IEEE 30-bus system with voltage deviation objective

Method	PSO-TVIW	PSO-TVAC	HPSO-TVAC	PSO-CF
Min VD	0.0922	0.1210	0.1136	0.0890
Avg. VD	0.1481	0.1529	0.1340	0.1160
Max VD	0.5675	0.1871	0.1615	0.3644
Std. dev. VD	0.1112	0.0153	0.0103	0.0404
P_{loss} (MW)	5.8452	5.3829	5.7269	5.8258
L_{max}	0.1481	0.1485	0.1484	0.1485
Avg. CPU time (s)	9.97	9.88	9.59	9.89

Table 6. Results by PSO methods for the IEEE 30-bus system with voltage stability index objective

Method	PSO-TVIW	PSO-TVAC	HPSO-TVAC	PSO-CF
Min L_{max}	0.1249	0.1248	0.1261	0.1247
Avg. L_{max}	0.1261	0.1262	0.1275	0.1265
Max L_{max}	0.1280	0.1293	0.1287	0.1281
Std. dev. L_{max}	0.0008	0.0009	0.0006	0.0008
P_{loss} (MW)	4.9186	4.8599	5.2558	5.0041
VD	1.9427	1.9174	1.6830	1.9429
Avg. CPU time (s)	13.42	13.39	13.05	13.39

Table 7. Comparison of best results for the IEEE 30-bus system

Method	Power loss (MW)	Voltage deviation (VD)	Stability index ($L_{i,max}$)
DE [11]	4.5550	0.0911	0.1246
CLPSO [15]	4.5615	-	-
PSO-TVIW	4.5129	0.0922	0.1249
PSO-TVAC	4.5356	0.1210	0.1248
HPSO-TVAC	4.5283	0.1136	0.1261
PSO-CF	4.5128	0.0890	0.1247

4.2 IEEE 118-bus system

In this system, the position and lower and upper limits for switchable capacitor banks, and lower and upper limits of control variables are given in [15]. The number of particles for the implemented PSO methods is set to 40.

The obtained results by the PSO methods for the system with different objectives similar to the case of IEEE 30 bus system are given in Tables 8, 9, and 10, respectively and the comparison of best results from methods for different objectives is given in Table 11. For the total power loss objective, the proposed PSO-CF can obtain less power loss than CLPSO and other PSO variants. For the voltage deviation, the PSO-CF method also obtains better optimal solution than that from other PSO variants while the best voltage stability index is nearly the same for PSO-CF and other PSO variants. For the computational time, the proposed PSO-CF is also vastly faster than that from CLPSO whose average computational time for this system is 1472 seconds.

5. CONCLUSION

In this paper, the PSO-CF method has been effectively and efficiently implemented for solving the ORPD problem. PSO-CF is a simple improvement of the conventional PSO method with convergence guaranteed for the method based on the mathematical theory. The proposed PSO-CF has been tested on the IEEE 30-bus and IEEE 118-bus systems with different objectives including power loss, voltage deviation, and voltage stability index. For the selected stopping criteria based on number of iterations, the obtained solutions by the proposed PSO-CF for test cases satisfy all constraints of the problem. Moreover, the convergence process of the PSO-CF method is also stable to the optimal solution of the problem. The test results have shown that proposed method can obtain total power loss, voltage deviation, or voltage stability index less than other PSO variants and other methods for the test cases. Therefore, the proposed PSO-CF could be a useful and powerful method for solving the ORPD problem.

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APPENDIX

The best solutions by PSO methods for the IEEE 30-bus system with different objectives are given in Tables A1, A2, and A3.

Table A1. Best solutions by PSO methods for the IEEE 30-bus system with power loss objective

Control variables	PSO-TVIW	PSO-TVAC	HPSO-TVAC	PSO-CF
V_{g1}	1.1000	1.1000	1.1000	1.1000
V_{g2}	1.0943	1.0957	1.0941	1.0944
V_{g5}	1.0748	1.0775	1.0745	1.0749
V_{g8}	1.0766	1.0792	1.0762	1.0767
V_{g11}	1.1000	1.1000	1.0996	1.1000
V_{g13}	1.1000	1.0970	1.1000	1.1000
T_{6-9}	1.0450	1.0199	1.0020	1.0435
T_{6-10}	0.9000	0.9401	0.9498	0.9000
T_{4-12}	0.9794	0.9764	0.9830	0.9794
T_{27-28}	0.9652	0.9643	0.9707	0.9647
Q_{c10}	5.0000	4.5982	2.3238	5.0000
Q_{c12}	4.9952	2.8184	2.8418	5.0000
Q_{c15}	5.0000	2.3724	3.6965	5.0000
Q_{c17}	5.0000	3.6676	4.9993	5.0000
Q_{c20}	4.0765	4.3809	3.1123	4.0041
Q_{c21}	5.0000	4.9146	4.9985	5.0000
Q_{c23}	2.5071	3.6527	3.5215	2.3834
Q_{c24}	5.0000	5.0000	4.9987	5.0000
Q_{c29}	2.2284	2.1226	2.3743	2.2176

Table A2. Best solutions by PSO methods for the IEEE 30-bus system with voltage deviation objective

Control variables	PSO-TVIW	PSO-TVAC	HPSO-TVAC	PSO-CF
V_{g1}	1.0090	1.0282	1.0117	1.0080
V_{g2}	1.0036	1.0256	1.0083	1.0030
V_{g5}	1.0184	1.0077	1.0169	1.0159
V_{g8}	1.0079	1.0014	1.0071	1.0078
V_{g11}	1.0240	1.0021	1.0707	1.0558
V_{g13}	1.0220	1.0046	1.0060	1.0059
T_{6-9}	1.0387	1.0125	1.0564	1.0780
T_{6-10}	0.9000	0.9118	0.9076	0.9000
T_{4-12}	0.9964	0.9617	0.9545	0.9799
T_{27-28}	0.9596	0.9663	0.9695	0.9654
Q_{c10}	3.1805	5.0000	1.5543	5.0000
Q_{c12}	0.0000	1.5065	1.4242	5.0000
Q_{c15}	4.9903	3.9931	2.5205	4.7892
Q_{c17}	1.5245	3.7785	1.6400	0.0000
Q_{c20}	5.0000	3.2593	5.0000	5.0000
Q_{c21}	5.0000	4.1425	1.8539	4.9069
Q_{c23}	5.0000	4.9820	3.3035	5.0000
Q_{c24}	4.1862	4.5450	4.5941	5.0000
Q_{c29}	1.6848	4.1272	3.5062	2.1107

Table A3. Best solutions by PSO methods for the IEEE 30-bus system with objective of stability index

Control variables	PSO-TVIW	PSO-TVAC	HPSO-TVAC	PSO-CF
V_{g1}	1.1000	1.1000	1.0979	1.1000
V_{g2}	1.0911	1.0934	1.0997	1.1000
V_{g5}	1.0440	1.0969	1.0500	1.1000
V_{g8}	1.0734	1.0970	1.0663	1.0766
V_{g11}	1.1000	1.1000	1.0561	1.1000
V_{g13}	1.1000	1.1000	1.0886	1.0834
T_{6-9}	0.9701	1.0935	0.9939	1.0040
T_{6-10}	0.9000	0.9000	1.0150	0.9000
T_{4-12}	0.9451	0.9579	0.9121	0.9182
T_{27-28}	0.9425	0.9651	0.9406	0.9414
Q_{c10}	3.7186	3.1409	3.7685	3.4792
Q_{c12}	2.2318	3.0186	4.6323	0.0000
Q_{c15}	0.5772	1.4347	2.6542	2.5747
Q_{c17}	0.0000	3.8498	2.6897	0.0061
Q_{c20}	2.3728	0.0000	2.8806	2.3822
Q_{c21}	2.6790	5.0000	2.1071	2.5272
Q_{c23}	0.1350	0.0000	3.1044	1.1154
Q_{c24}	1.2181	2.1733	2.1797	0.0000
Q_{c29}	1.3609	2.2708	3.5843	0.0000

The Analysis of Failed-type and Symptom of High Voltage Circuit Breaker for Performance Assessment

Thanapong Suwanasri, Sakda Nobnorp, Sarawut Wattanawongpitak, and Cattareeya Suwanasri

Abstract— *The performance of high voltage equipment in electrical power system should be assessed and clearly identified as supported reasons for planning the renovation task of electrical asset. Thus, the performance assessment based on failed-type and symptom for high voltage circuit breakers rated as of 115 kV, 230 kV and 500 kV are focused in this work. The scattering failure events are systematically recorded and analyzed by using statistical techniques. Since numbers of circuit breakers from each manufacturer are different, the failure rates of every manufacturer are calculated and compared. After that the failure evaluation is performed. Then, the symptoms of failure are classified for each voltage level. The known failure rate and symptom are used as criteria for performance evaluation of those high voltage circuit breakers. The proposed criteria can also used with other high voltage equipment in the power system.*

Keywords— **Performance assessment, power circuit breaker, failed-type, symptoms, failure rates.**

1. INTRODUCTION

The major equipments in high voltage substation are power transformer, power circuit breaker, disconnecting switch, and instruments transformer. One of the most importance equipment is power circuit breaker. The power circuit breaker has its functions for switching or disconnecting the operating circuit for maintenance purpose as well as interrupting the fault current for preventing the blackout in power system. The power circuit breakers with high failure statistic should be analyzed intensively for preventing unpredictable failure and evaluating optimal operation and maintenance in order to determine maintenance schedule and save the maintenance costs of utility. Various numbers and technologies of power circuit breakers were installed in the power system. The deterioration of power circuit breakers depends on equipment quality, operation such as load stress, maintenance, surrounding environment such as temperature, moisture, pollution, and etc. All aforementioned problems are the main effects to the equipment performance. They also cause the growing of the deterioration process. If the maintenance activity has not been approached properly, the equipment may encounter minor failures and extend to major failures in the future. Therefore, the major and minor failures of the specified part of equipment and specified manufacturer should be determined to prevent the huge disaster and help for maintenance decision making.

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This paper, presents the failure analysis of power circuit breakers in different voltage levels by classifying the minor and major failures in term of symptoms, and failed-type. The results show explicitly the causes of major or minor failures, and shown implicitly incorrect operation or inadequate maintenance. Then, the correct maintenance schedule or renovation of equipment with the minimum cost can be applied. In addition, the utility can differentiate the best manufacturer of the specified equipment.

2. FAILURE STATISTICS

Failure statistics is the number of event and data recorded in any utility in a given time over the long period. The failure data of power circuit breakers in high voltage substations of a utility in Thailand were recorded from year 1989 to 2011. However, the data has not been statistically recorded and analyzed. Consequently, the manufacturers, models, or parts that produce high failure rates cannot be predictable. From this reason, the failure statistic analysis should be achieved for indicating the performance of power circuit breakers according to visible deterioration such as symptoms, failed-types, and obsolescence as well as invisible deterioration such as aging and in-service stress. In this paper, only the first two mentioned criteria of the visible deterioration are focused. The historical failures are divided into two types: major and minor failures.

The major failures are the events occurred during circuit breakers operated and affected on surrounding equipment and caused power system outages. The minor failures were found during maintenance activities or visual inspection from operators [2]. Therefore, the symptom and failed-types can be analyzed in term of major failure and minor failure, respectively. The failure rate can be calculated as in Eq. (1).

$$Failure\ Rate\ [freq./year] = \frac{Number\ of\ failure}{Total\ usage\ time} \qquad (1)$$

The failure rate represents the symptoms frequency per year of equipment of any manufacturer. Because of the power circuit breakers of any manufactures are not identical; the failure rate of each manufacturer should be calculated with the same basis as per 100 CB. Therefore, the Eq. (1) is modified as in Eq. (2).

$$Failure\ Rate\ [\,freq./100\ CB\ year\,]\ =\ Failure\ Rate\ \times 100 \qquad (2)$$

The failure rate can help the utility for choosing the better manufacturers with the better quality and performance.

3. FAILURE ANALYSIS AND RESULTS

The two aforementioned criteria, as symptom and failed-type, are statistically considered by classifying into the major and minor symptom of failures.

3.1 Failed-types Analysis

3.1.1. Failure Events

The failure events occurred of different manufacturers at different voltage levels were analyzed as follows.

In Table 1, the numbers of failures of a total 1,718 power circuit breakers at 115 kV level from 19 manufacturers are represented in form of manufacturers A to S. The total major and minor failure events occurred 344 and 542 times, respectively. The manufacturer A obtains the highest numbers of major and minor failures, which are 124 and 224 failures of the total 473 circuit breakers installed in the system. Although, the manufacturer A encounters the highest failure rate but it cannot be concluded that its devices has a poor performance. Because of the total number of installed devices is the highest. Similarly, the other manufacturers as F, G, K, L, M and N provide the failure rate significantly lower than manufacturer A. But it is unable to conclude that these manufacturers get better performance than manufacturer A, because of the number of installed devices are less than manufacturer A. In addition, they were probably not installed in the utility's high voltage substations for long periods [1].

Similarly, Table 2 and Table 3 present the number of failures from 15 manufacturers of the circuit breakers at 230 kV and from 8 manufacturers at 500 kV. In Table 2, by considering reliability perspective, the manufacturer B shows its worst performance. Because only 8 devices were installed at 230 kV high voltage substation but major failures occurred up to 40 times. However, these devices have been disconnected and replaced by the manufacturer E, which produces the better performance.

In Table 3, at 500 kV high voltage substations connected to power plant, almost of the power circuit breakers were not installed in transmission system. Majority, these power circuit breakers were not operated under high loading situation and not switched frequently. Then, it should obtain fewer failures; however, some manufacturers still obtain high failure rates such as manufacturer U with 9 major and 31 minor failures of the total 12 circuit breakers installed in substation.

Table 1. Number of Failures of Circuit Breakers in 115 kV High Voltage Substations

Manufacturers	Number of devices	Number of failures	
		Major failures	Minor failures
A	473	124	224
B	174	32	48
C	19	0	3
D	19	0	1
E	80	6	4
F	7	7	0
G	1	0	1
H	32	13	25
I	195	17	18
J	11	0	3
K	13	12	0
L	4	2	1
M	1	0	1
N	5	3	11
O	180	60	108
P	36	14	28
Q	64	2	5
R	197	14	26
S	207	38	35
Grand Total	1718	344	542

Table 2. Number of Failures of Circuit Breakers in 230 kV High Voltage Substations

Manufacturers	Number of devices	Number of failures	
		Major failures	Minor failures
A	289	62	84
B	8	40	24
D	5	0	1
E	8	0	0
F	3	1	0
H	2	2	1
I	141	13	14
L	12	18	20
N	92	25	105
O	22	19	24
P	44	19	55
Q	244	37	64
R	163	16	46
S	33	8	8
T	1	2	2
Grand Total	1059	262	448

Table 3. Number of Failures of Circuit Breakers in 500 kV High Voltage Substations

Manufacturers	Number of devices	Number of failures	
		Major failures	Minor failures
A	40	12	16
D	2	0	1
J	14	0	0
N	8	0	1
O	6	0	3
Q	36	2	2
U	12	9	31
W	6	1	10
Grand Total	124	23	64

3.1.2. Failure Rate Calculation

From failure records, the failure rates of different circuit breakers from different manufacturers can be calculated in form of frequency per 100 CB-year of failure rate [3].

Fig. 1 presents failure rates of 115 kV circuit breakers. Significantly, the minor failures occurred with manufacturers A, G, M, N and Q. For example, manufacturer Q encounters failure rate as of 4.2414 frequencies per 100 CB-year, which is the highest rate in this voltage level. The manufacturer G and M produced the failure rate as of 2.6316 and 3.4483 frequencies per 100 CB-year but the major failures have never occurred with them. The major failure rate of manufacturer L is 2.9412 that is the highest major failure rate of 115 kV substations; there is also minor failure occurred. Likewise the manufacturers F and K encounter 2.0772 and 2.8037 of major failure rates while there is no minor failure for both.

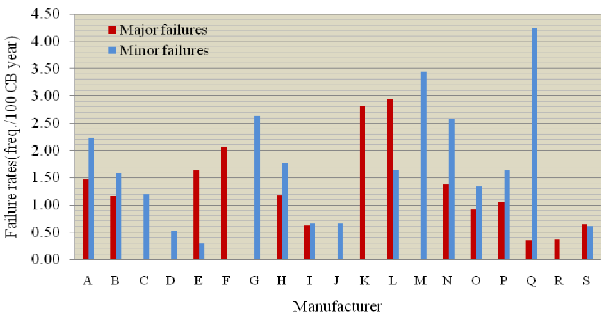

Fig.1. Failure Rates for 115 kV Circuit Breakers

Fig. 2 shows failure rates of 230 kV circuit breakers. The manufacturer B provides the highest major failure as 4.7114 times per 100 CB-year. These devices were uninstalled from the substation. The manufacturer L obtains 4.1096 major and 4.5558 minor failure rates from a total of 18 devices, which is considered as a high failure rates. The manufacturer T also obtains high failure rate because there is only 1 device was installed. Another manufacturer H encounters high major failures rate as 3.4483.

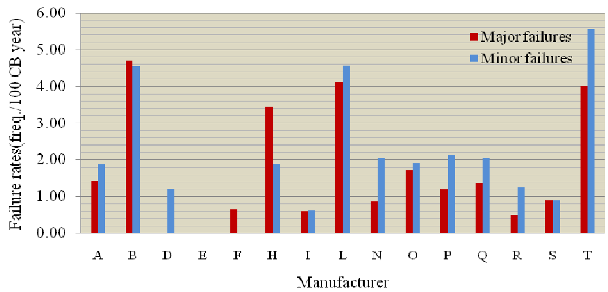

Fig.2. Failure Rates for 230 kV Circuit Breakers

Fig. 3 shows the 500 kV circuit breakers with only 8 manufacturers. The manufacturer W comes up with 1.5625 and 8.3333 for major and minor failure rates. The manufacturer U gets 2.0501 and 3.3991 for major and minor failure rates whereas the manufacturer A gets 1.6807 and 2.0513 for major and minor failure rate. There is no major failure for manufacturer D and O but there is minor failure rate. Comparing such failure rates with obtained from other manufacturers, there equipment are in lower quality.

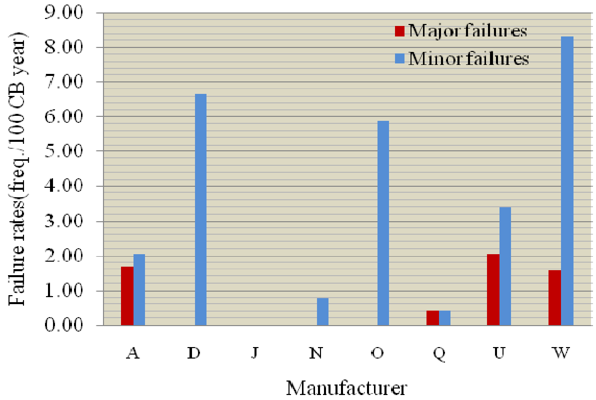

Fig.3. Failure Rates for 500 kV Circuit Breaker

Summarily, from the failure rates of power circuit breakers in three voltage levels interestingly, the manufacturer A is the most popular for each voltage level with its low failure rates. In the same way, the manufacturer R is largely installed in 115 kV and 230 kV systems with the low failure rates. That means the failure rate can be acceptable. Failure rates show the quality and performance of each manufacturer. However, it also depends on the operation and maintenance.

3.2 Symptom Analysis

The failure statistics are classified into major and minor symptoms [4].

3.2.1. Major Symptoms

Due to the severe effect when the failure occurred, the major symptoms must be considered into 13 categories as (1) Does not closed on command, (2) Does not opens on command, (3) Alarm & lockout in open or closed, (4) High contact resistance, (5) Opens without command, (6) Breakdown across open pole (internal), (7) Breakdown to earth, (8) Insulation lower than standard, (9) Operation timing does not standard, (10) Does not break the current, (11) Does not carry the current, (12) Does not make the current, and (13) Other. Fig. 4 to Fig. 6 show the major symptoms of power circuit breakers. The most frequent symptom is "Does not closed on command". Whereas the most cause of symptom are incorrect operation and maintenance, inadequate instruction for erection, stresses beyond those specified, bad contact in auxiliary control circuit and another cause that unknown [4].

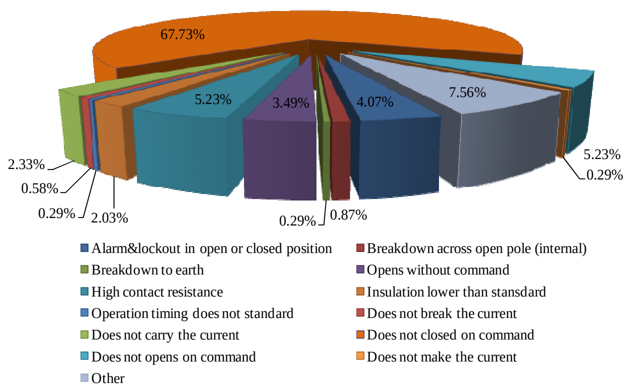

Fig.4. Major Symptoms of 115 kV Circuit Breakers

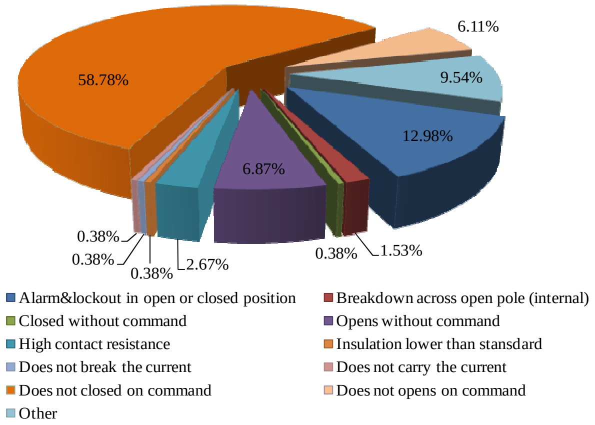

Fig.5. Major Symptoms of 230 kV Circuit Breakers

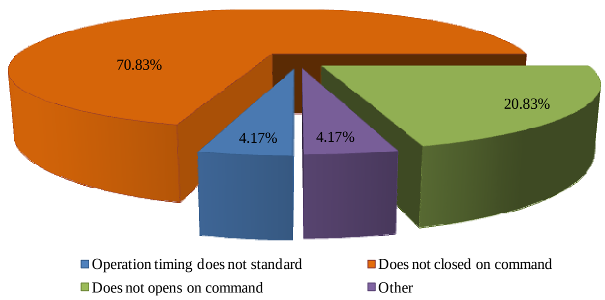

Fig.6. Major Symptoms of 500 kV Circuit Breakers

3.2.2. Minor Symptoms

The minor symptoms are classified into 5 categories as (1) Air or hydraulic oil leakage in the operating mechanism, (2) Change in functional characteristics, (3) Small SF6 leakage due to nut is not tight, (4) Small SF6 leakage due to corrosion and (5) Other. The most minor symptom in 115 kV voltage levels is "Air or hydraulic oil leakage in the operating mechanism". In a part of the other symptoms, the mostly symptoms may be not severe or severe such as breaker intermediate, does not charge spring, bad contact limit switch, counter failed and explosion event, etc [4].

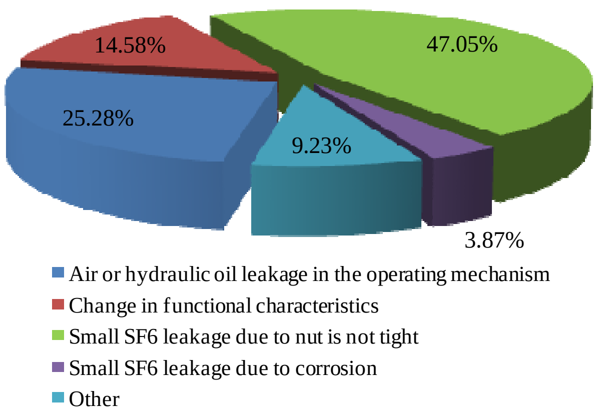

Fig.7. Minor Symptoms of 115 kV Circuit Breakers

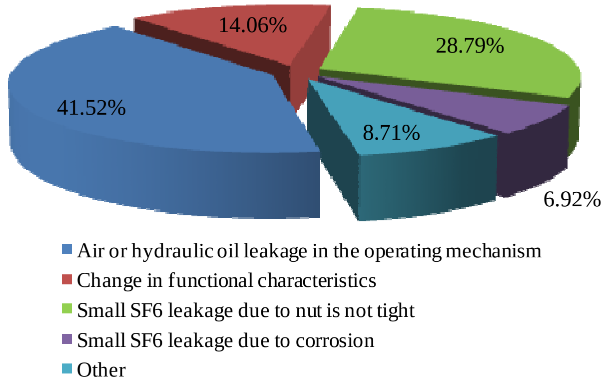

Fig.8. Minor Symptoms of 230 kV Circuit Breakers

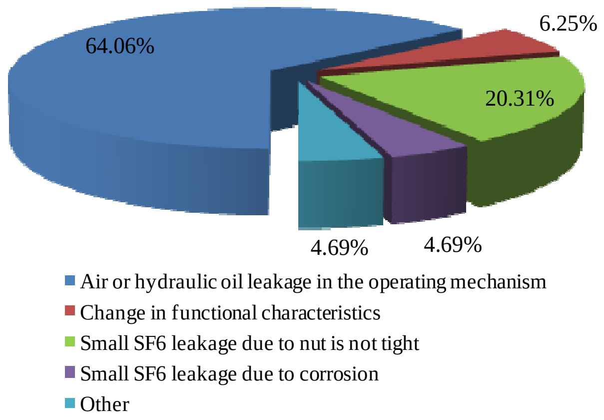

Fig.9. Minor Symptoms of 500 kV Circuit Breakers

4. RESULT DISCUSSION

Statistical failure records of HV circuit breakers are very important for any utility because the fail in equipment can cause a severe damage to the power system. Therefore, this paper presents the analyses on historical failures based on failed-types and symptoms of power circuit breakers in high voltage substations rated as of 115 kV, 230 kV and 500 kV in a Thai utility. The failed-types and symptoms are classified into major and minor failure criteria. For failed-type analysis, failure rates of circuit breakers produced by different manufacturers and installed in three voltage levels are analyzed and ranked. The analyses show the performance of equipment of each manufacturer based on failure frequency per 100 CB-year. The reaults can imply that the manufaturers with the higher failure rates produce the equipment in lower performance. Consequently, the utility shold strickly consider those manufaturers for the future installating of the circuit breakers in substation or even planning of the proper maintenance schedule.

For the symptom analysis, it is similarly classified into major and minor symptoms of the same historical failures of HV circuit breakers in high voltage substations. In major symptom of failure of circuit breakers in all voltage levels is "Does not closed on command". Whereas the minor symptoms of failure are different for each voltage level. For 115 kV circuit breaker, "small SF_6 leakage due to loosen bolt and nutis" is the main cause of minor symptom with less problem in operating mechanism parts due to its small and compact size e.g. motor charge spring. On the contrary, 230 kV and 500 kV circuit breakers, the main cause of minor symptom is “air or hydraulic leakage in operating mechanism” because of their multi-interrupter construction, which requires large size and highly pressurized operating mechanism.

5. CONCLUSION

The historical failure events of circuit breakers in 115 kV, 230 kV and 500 kV, which are scattering and paper-based in nature, are systematically recorded in the central database. After setting up the central database, the number of failure events and service year of each manufacturer are known. Thus, the failure rate of circuit breakers according to each manufacturer can be subsequently calculated. The circuit breakers from manufacturers with high failure rate requires more attention than the one with lower failure rate in term of maintenance action, maintenance plan and spare part management. Moreover, the symptom as major and minor symptoms for all voltage levels is determined. The known symptom from using experiences is used as a valuable lesson to avoid repeated failure. The main symptom is originated from operating mechanism especially 230 kV and 500 kV circuit breakers due to multi-interrupter construction. Hence the operating mechanism should be intensively focused in maintenance in order to improve the reliable operation of this equipment.

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NOTES FOR AUTHORS

Editorial Policy

In the Greater Mekong Subregion, home to about 250 million people, environmental degradation - including the decline of natural resources and ecosystems will definitely impact on the marginalized groups in society - the poor, the border communities especially women and children and indigenous peoples. The complexity of the challenges are revealed in the current trends in land and forest degradation and desertification, the numerous demands made on the Mekong river - to provide water for industrial and agricultural development, to sustain subsistence fishing, for transport, to maintain delicate ecological and hydrological balance, etc., the widespread loss of biological diversity due to economic activities, climate change and its impacts on the agricultural and river basin systems, and other forms of crises owning to conflicts over access to shared resources. The *GMSARN International Journal* is dedicated to advance knowledge in energy, environment, natural resource management and economical development by the vigorous examination and analysis of theories and good practices, and to encourage innovations needed to establish a successful approach to solve an identified problem.

The *GMSARN International Journal* is a quarterly journal published by GMSARN in March, June, September and December of each year. Papers related to energy, environment, natural resource management, and economical development are published. The papers are reviewed by world renowned referees.

Preparation Guidelines

1. The manuscript should be written in English and the desired of contents is: Title, Author's name, affiliation, and address; Abstract, complete in itself and not exceeding 200 words; Text, divided into sections, each with a separate heading; Acknowledgments; References; and Appendices. The standard International System of Units (SI) should be used.

2. Illustrations (i.e., graphs, charts, drawings, sketches, and diagrams) should be submitted on separate sheets ready for direct reproduction. All illustrations should be numbered consecutively and given proper legends. A list of illustrations should be included in the manuscript. The font of the captions, legends, and other text in the illustrations should be Times New Roman. Legends should use capital letters for the first letter of the first word only and use lower case for the rest of the words. All symbols must be italicized, e.g., α, θ, Q_{wt}. Photographs should be black and white glossy prints; but good color photographs are acceptable.

3. Each reference should be numbered sequentially and these numbers should appear in square brackets in the text, e.g. [1], [2, 3], [4]–[6]. All publications cited in the text should be presented in a list of full references in the Reference section as they appear in the text (not in alphabetical order). Typical examples of references are as follows:

   - **Book references** should contain: name of author(s); year of publication; title; edition; location and publisher. Typical example: [2] Baker, P.R. 1978. Biogas for Cooking Stoves. London: Chapman and Hall.
   - **Journal references** should contains: name of author(s); year of publication; article title; journal name; volume; issue number; and page numbers. For example: Mayer, B.A.; Mitchell, J.W.; and El-Wakil, M.M. 1982. Convective heat transfer in veetrough liner concentrators. Solar Energy 28 (1): 33-40.
   - **Proceedings reference** example: [3] Mayer, A. and Biscaglia, S. 1989. Modelling and analysis of lead acid battery operation. Proceedings of the Ninth EC PV Solar Conference. Reiburg, Germany, 25-29 September. London: Kluwer Academic Publishers.
   - **Technical paper** reference example: [4] Mead, J.V. 1992. Looking at old photographs: Investigating the teacher tales that novice teachers bring with them. Report No. NCRTL-RR-92-4. East Lansing, MI: National Center for Research on Teacher Learning. (ERIC Document Reproduction Service No. ED346082).
   - **Online journal** reference example: [5] Tung, F. Y.-T., and Bowen, S. W. 1998. Targeted inhibition of hepatitis B virus gene expression: A gene therapy approach. Frontiers in Bioscience [On-line serial], 3. Retrieved February 14, 2005 from http://www.bioscience.org/1998/v3/a/tung/a11-15.htm.

4. Manuscript can be uploaded to the website or sent by email. In case of hard copy, three copies of the manuscript should be initially submitted for review. The results of the review along with the referees' comments will be sent to the corresponding author in due course. At the time of final submission, one copy of the manuscript and illustrations (original) should be submitted with the diskette. Please look at the author guide for detail.

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