Indonesian Journal of Electrical Engineering and Computer Science
Vol. 34, No. 2, May 2024, pp. 687~696
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v34.i2.pp687-696

A critical evaluation of DC microgrid implementation in Indonesia: opportunities and challenges

Levin Halim[1], Pinto Anugrah[2], Aditya Kurniawan[3], Khairuddin Karim[4]
[1]Department of Electrical Engineering, Faculty of Industrial Technology, Parahyangan Catholic University, Bandung, Indonesia
[2]Department of Electrical Engineering, Faculty of Engineering, Universitas Andalas, Padang, Indonesia
[3]Department of Heavy Equipment Technology, Akademi Teknik Alat Berat Indonesia, Malang, Indonesia
[4]Department of Electrical Engineering, State Polytechnic of Samarinda, Samarinda, Indonesia

Article Info

Article history:

Received Dec 18, 2023
Revised Feb 7, 2024
Accepted Feb 16, 2024

Keywords:

Challenges
DC microgrids
Indonesia
Opportunities
Renewable energy

ABSTRACT

This study thoroughly investigates the potential of direct current (DC) microgrids to enhance electricity access in rural and remote areas of Indonesia that continue to face significant obstacles despite ongoing national electrification efforts. Utilizing a mixed-methods approach, this research comprehensively evaluates socio-economic and technical factors that influence the adoption of DC microgrids. The results indicate that DC microgrids offer significant potential for enhancing energy access, reliability, and sustainability, particularly when combined with renewable energy sources. This aligns with Indonesia's move towards renewable energy. Nevertheless, the analysis identifies significant obstacles, such as the substantial initial investment, the requirement for complete regulatory frameworks, and the technological complexities that need to be conquered. In conclusion, DC microgrids present a promising solution for rural electrification. However, the implementation requires a strategy that emphasizes strategic investments, policy innovation, and capacity-building initiatives. This research significantly contributes to the study of sustainable energy by evaluating the criticality of integrating policies and technology for implementing DC microgrids as a key factor in achieving sustainable energy access in Indonesia.

Corresponding Author:

Levin Halim
Department of Electrical Engineering, Faculty of Industrial Technology, Parahyangan Catholic University
Street of Ciumbuleuit No. 94, Bandung, 40141, Indonesia
Email: halimlevin@unpar.ac.id

1. INTRODUCTION

The electrification rate in Indonesia has increased significantly in recent years, with a predicted annual increase [1]. Nonetheless, progress on electrification has stagnated since 2018, particularly in rural and remote areas [2]. This deficiency is emphasized by the fact that Indonesia's rural electrification coverage totaled 40%, much below the regional average [3], even though the country had reached a 99.2% electrification rate by 2020. The impact of inte-rgovernmental transfers on infrastructure spending in Indonesia highlights the ne-ed for purposeful investment to address energy access disparities [4]. Additionally, the study underscores how global and national institutional dynamics influence rural electrification policies in Indonesia, pointing to the necessity of enhancing energy accessibility [5].

The implementation of direct current (DC) microgrids in Indonesia presents a feasible approach to addre-ssing several challenges [6]–[8]. Microgrids depend greatly on household appliances and distributed generation (DG). They depend extensively on power electronics and interact closely with DC-powered electronic devices including computers, fluorescent lights, also industrial and domestic equipment [9]. DC microgrids could supply remote areas with reliable and sustainable electricity supplies [10]‒[12], consequently, the nation's reliance on fossil fuels is reduced [13], [14]. Previous studies [15] show that DC microgrids are more reliable and efficient, especially with electronic loads and renewable sources. Another study [16] shows that AC-DC hybrid microgrids improve voltage stability, implying that the choice between DC and hybrid microgrids should depend on the context to address energy disparities and achieve sustainable energy objectives in Indonesia. DC microgrids have gained significant attention due to their potential advantages such as higher efficiency, absence of reactive power and harmonics, and lower conversion losses compared to AC microgrids [17]. A typical DC microgrid structure is shown in Figure 1.

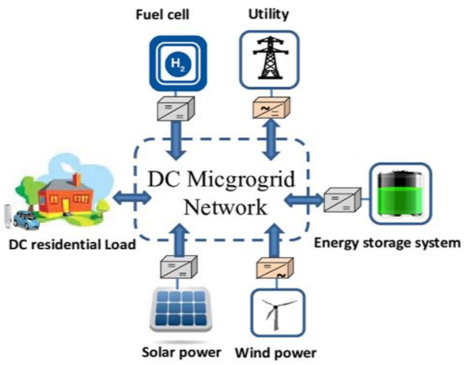

Figure 1. General structure of a DC microgrid [18]

Despite the apparent advantages, there is a significant research gap regarding DC microgrid implementation in Indonesia. The existing literature [19]‒[25] mainly concentrates on the technical and theoretical aspects while providing limited exploration of the practical application of DC microgrids in the Indonesian archipelago. On the other hand, despite possible regulatory obstacles, microgrids can participate in regional electricity markets through various models, providing additional benefits to their owners [26], which shows that AC microgrids can be adapted for DC microgrids, indicating the potential for leveraging knowledge from AC microgrids to enhance DC microgrid operations [27]. Furthermore, a full evaluation of DC microgrid planning, operation, and control is noted as a lack in the available literature [28]. The benefits of hybrid AC/DC microgrids highlight economy and efficiency, implying created hybrid solutions for applications [29]. Research shows economic DC microgrid operation without complex, costly optimization [30]. Moreover, hybrid AC/DC microgrids potentially integrate AC and DC generation and loads with minimal conversion, indicating enhanced efficiency and reliability [31]. In literature, traditional hierarchical control approaches using DC microgrids frequently proved to be enabling mechanisms for the realization of the intelligent microgrids with a hold on advanced microgrid structures [32]. According to the research, DC microgrids achieve success by using single-line-oriented control mechanisms that involve varied generation, storage, converters, and load [33]. This emphasizes the necessity of advanced controls to adjust different components of the system and facilitating the smooth transition to the DC microgrids.

This research of DC microgrid implementation in Indonesia tackles the socio-economic concerns and technological obstacles, and offers solutions through policies and government initiatives, making new contributions. The opportunity and challenge of using DC microgrids is this research's focus because they are likely to help Indonesia achieving rural electrification and sustainable energy goal. This study provides the basis for equitable and sustainable energy in Indonesia, rendering the issue more profound notably for rural and remote regions. An overview of the Indonesian electricity system for further discussions will follow. The current infrastructure and facilities are assessed which then gives an overview of the existing strengths and areas that need adjustments. Assessment of the work of the government and its policy landscape is the next part. Eventually, an assessment is carried out which discovers the opportunities and challenges of using DC microgrid.

2. METHOD

This research specifically examines the possibilities and impacts of DC microgrids in Indonesia. It peremptory a qualitative analysis of electrical sector, laws, social and economic aspects. The research looks at the opportunity for the countries DC microgrids scenario given the circumstances of Indonesia. The data was obtained from the academic papers, government literature, case studies, experts, and current initiatives. The assessment topic was in the sphere of technological progress, regulations, real implementations, and specific problems in Indonesia's energy sector. This study tried to be as comprehensive as possible from many aspects to evaluate the implementation of DC microgrids in Indonesia.

Firstly, international journals and research papers were reviewed with the aim to gather the extensive information on the global deployment of DC microgrid technology and in particular, its application in Indonesia. Therefore, further an in-depth assessment of Indonesia's electricity infrastructure was done, with an emphasis on the differences between urban compared to rural areas. The research team applied a mixed-methods approach by combining qualitative and quantitative tools such as case study analysis, policy evaluation and technical reports on existent DC microgrid implementation.

This research investigating the multiple dimensions of potential DC microgrid implementation in Indonesia will be done using a combination of qualitative and quantitative methods to give a fully comprehensible final result. The employment of mixed techniques was based on the fact that the research subject was multifaceted, therefore allowing us to investigate the technical and socio-economic aspects. Qualitative analysis allowed to see the qualitative side of policy and social impact, and quantitative techniques got us to justifications of the technical and infrastructure basis. This implemention of integrated approach that encompasses all issues and opportunities of DC microgrids in electrical environment in the country will make this thesis both rigorous and reliable.

A detailed investigation was carried out on the electrical infrastructure in Indonesia, focusing on both urban and rural areas. This thorough examination was informed by a review of relevant literature and government sources, providing valuable data on electrification rates, infrastructure advancements, and the integration of sustainable energy sources. To further enhance our understanding, a comparative analysis of DC microgrid initiatives was also conducted, both within Indonesia and on a global scale, to identify their strengths and limitations.

3. RESULT AND DISCUSSION

3.1. Overview of Indonesian electrical system

The Indonesian Archipelago unique structure has developed a wide variation of electrical networks that ranges from the busy urban centers to the secluded rural locales [34]. Currently, nearly all of these networks run on AC power as a standard means for delivering electricity [35], [36], while significant progress has already been made in the direction of utilizing DC systems. This phenomenon is especially obvious in off-grid or remote areas, where renewable energy sources such as solar panels, are more often used [37], [38]. The electrical system of Indonesia comprises a series of regional grids supporting the archipelago's energy needs. The most expansive network, serving the greater part of the population, is the Java-Bali Grid, commonly known as the Jawa-Madura-Bali (JAMALI) system [39], with a demand of 177,692.43 GWh and a peak load of 40,059.74 MW in 2019 [40]. This subsystem accounts for about 75% of the country's entire energy sales, highlighting its significance in the national energy scene [41].

While urban areas in Indonesia experience a relatively high electrification rate, rural areas, particularly those in remote islands, have fallen behind [42], [43]. The vast geographic distance presents significant logistical challenges in extending the national grid. As a result, alternative solutions such as microgrids are being explored, which can function either independently or in cooperation with the primary grid. To accommodate the projected rise in renewable energy, particularly from solar photovoltaics (PVs), the current assets in Java-Bali and Sumatra have been identified as capable of supporting a 10% proportion of solar-generated electricity by 2025 [44]. This objective necessitates an increase in solar PV capacity to 17.7 GW, a substantial rise from the 2.8 GW outlined in the RUPTL [45]. At this stage, the IEA states that no extra investment is needed for additional grids or storage capacity. However, updates to operating practices and the ability to monitor and control solar PV plants are necessary [46]. On the other hand, Indonesia possesses significant prospects for renewable energy, especially through solar and hydroelectric power [47]. Integrating these sources of clean energy is more feasible with DC systems as they inherently produce DC electricity [48]–[50], which will decrease the need for energy conversion, which ultimately improves overall system efficiency.

3.2. Current infrastructure and capacity

Indonesia's current electrical infrastructure displays a noticeable divide between urban and rural areas. Urban areas feature an electrical network with a well-established alternating current (AC) grid system [51]. This strong infrastructure can efficiently meet the dense energy needs of urban populations, allowing for a high degree of electrification. However, the situation is different in the rural and remote regions of Indonesia's extensive archipelago. In these areas, the electrical infrastructure varies from underdeveloped to almost nonexistent, resulting in a substantial disparity in energy accessibility [2]. The installed capacity for solar power plants and hydropower plants in each province in Indonesia is shown in Figure 2.

Figure 2(a) shows the 2020 solar power plant installation capacity by region. Sumatra has the most solar energy capacity, reflecting significant investments. In contrast, Figure 2(b) shows hydropower plant capacity, with Sulawesi, implying a purposeful focus on hydroelectric power generation. However, because these areas lack pre-existing infrastructure, there are numerous challenges and high costs involved in providing stable power. But they also offer a special opportunity to avoid the disadvantages of traditional AC systems. These areas make ideal locations for DC microgrids as well, which can be planned to best utilize renewable energy resources such as hydro and solar in meeting local power requirements.

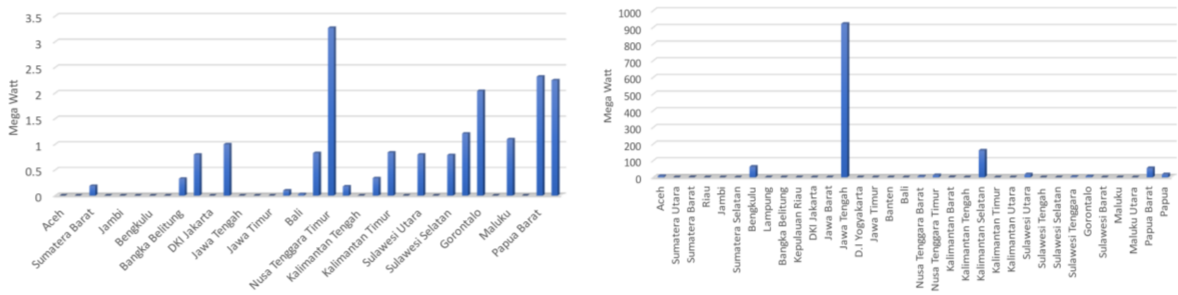

Figure 2. Installed capacity in 2020 (a) solar power plant and (b) hydro power plant [52]

The development of Indonesia's renewable energy is an important part of the modernization plans for its electrical infrastructure [53], [54]. It is rich in renewable resources such as solar, wind, and hydro, particularly on the rural portions of the mainland, and outlying islands. Hence in this situation, the natural compatibility of DC microgrids with renewable energy sources becomes a substantial advantage. DC power created by solar panels and wind turbines can be fed directly into DC microgrids. This is all the more easy as these plants supply their own AC-DC converters [47], [53], [54]. Thus, the study [55] showed that a DC microgrid making use of solar photovoltaics can greatly increase energy capture efficiency.

Indonesia's level of investment and technological readiness is critically important to the implementation of DC microgrids. While the upfront costs of building these microgrids are high, in terms of time their benefits include enhanced efficiency and lower transmission losses as well as greater resilience. These factors make them highly recommended [56], [57]. However, technological readiness varies widely in Indonesia from the availability and affordability of critical components such as inverters, storage systems, and advanced controls. Local microgrid system manufacturing skills are also needed for sustainable and scalable implementation. Local production lowers prices, improves the supply chain, and reduces import expenses. In contrast, an investment plan that combines financial resources with human capital development and supports policies to collaborate with technology providers and research institutions is needed. Indonesia needs a holistic approach that boosts local manufacturing and supply chain efficiency and attracts investment to achieve long-term, fair universal energy access.

Moreover, the current policy framework and institutional infrastructure have a powerful influence on the development of DC microgrids in Indonesia [2], [58]. The development of renewable energy policy in Indonesia brings to the forefront the need for comprehensive legislation and international cooperation aimed at creating safe, uniform frameworks for DC microgrids. This will make implementation effective and consistent with international environmental objectives. These rural and remote regions offer a unique opportunity for DC microgrid application due to their underdeveloped electrical infrastructures and plentiful renewable energy supplies. With DC microgrids as the long-term solution for rural electrification, there would be no more need to expand AC grids region by region. However, the implementation depends on surmounting obstacles, including uneven technology maturity and insufficient local manufacturing. Also, to establish the preconditions for widespread acceptance and development of DC microgrid infrastructure, we should create a conducive policy environment through public-private and international cooperation.

3.3. Government initiative

The Indonesian government has been instrumental, in promoting the adoption of DC microgrid technology through the implementation of policies and laws. Their strong dedication to renewable energy along with targets, for increasing energy production forms the core of these initiatives [59]. DC microgrids offer a solution, for providing electricity to remote locations. The Indonesian government has implemented regulations, such as introducing incentives to promote the development of energy. This includes offering benefits adjusting tariffs and providing tax exemptions to facilitate the adoption of renewable energy solutions in rural areas while keeping costs manageable.

The Indonesian government also has been actively working towards promoting DC microgrid technology as a component of their plan to improve energy access and infrastructure specifically in remote and rural regions. They have implemented the "Bright Indonesia" initiative, intending to provide electricity to the remaining 15% of the population who currently do not have access, to grid services [60]. The Indonesian government has also enacted a policy "accelerating electrification in rural areas" aiming to encourage sector investments and the creation of microgrids, in areas [61]. This approach has played a role in encouraging increased involvement, from the sector, in microgrid projects. These endeavors are receiving backing.

On the other hand, the U.S. Treasury Secretary and Indonesian Finance Minister signed the $649 million Indonesia Infrastructure and Finance Compact, a collaboration between the U.S. Government's millennium challenge corporation (MCC) and the Government of Indonesia [62]. This five-year grant and $49 million from the Indonesian government support the just energy transition partnership and climate-resilient infrastructure. The focus is on improving transportation and logistics infrastructure funding and MSMEs' access to finance.

DC microgrids in Indonesia have received no financial incentives or subsidies recently. Renewable energy and infrastructure development have gained investment and enthusiasm nationwide, however DC microgrid-focused projects are not listed. Indonesia lacks government-led DC microgrid technology capacity-building programs, highlighting the need for targeted education and training to address technical, operational, and maintenance challenges for successful and sustainable rural electrification projects.

Through international cooperation, Indonesia will improve the creation and use of DC microgrids. Cooperative research, agreements to share technology, and investments in infrastructure all help to share technology and information. Indonesia will get DC microgrid technologies and people to work on them through international partnerships, especially in remote places. Through training and sharing of information, this cooperation would make Indonesian professionals better. Indonesia could learn a lot from how other countries have set up and used DC microgrids. While DC microgrid technology lacks financial incentives or capacity-building programs, the renewable energy industry will grow, needing remote DC microgrid systems. Global collaborations will assist Indonesia's transition to sustainable energy by sharing technology and knowledge. More focused government action is needed to implement DC microgrids, which bridge infrastructure gaps and create a resilient, sustainable energy future.

3.4. Opportunities and challenges

Implementing DC microgrids in Indonesia presents several technical obstacles, with the primary challenge being the compatibility of existing infrastructure with new DC technologies [63]. Since AC systems are mostly used in Indonesia, switching to DC microgrids would need major changes to grid infrastructure, end-user appliances, and industrial equipment. The huge Indonesian archipelago, with islands with varying electrical infrastructure and many communities still using diesel generators, makes the situation more challenging [64].

Energy storage presents a significant technical challenge for DC microgrids that rely on intermittent renewable energy sources like solar photovoltaic panels and wind turbines [65]. The extra energy produced at peak periods must be stored and used during low power generation times to maintain a steady supply of power [66]. This region is located near the equator which means it has a promising future in solar energy hence there is a need for cheap batteries, especially in solar photovoltaic power plant context.

The large up-front costs of installing DC microgrids with their associated energy storage limit economic feasibility [67]. Indonesian DC microgrids and energy storage systems face financial issues due to the lack of a comprehensive tariff and subsidy legislative framework. Introducing DC microgrids in rural and isolated regions of Indonesia can effectively address social and cultural obstacles. For instance, access to electricity may enable businesses or schools to operate late affecting family routines [68]–[70].

To effectively implement DC microgrids in Indonesia, there should be a culturally sensitive strategy. This strategy should therefore include community involvement in planning, awareness campaigns, and respect for local customs to ensure the implementation of microgrids into the social fabric. Indonesia has scalable energy solutions in the form of DC microgrids that may be expanded modularly to satisfy the increasing energy demands of emerging rural areas. This scalability is especially important in Indonesia, where energy needs vary greatly throughout the country's islands [71]. As a result of the dependability and efficiency, small-scale systems can be copied or extended in similar systems [72]–[74].

DC microgrid implementation in Indonesia has the potential to boost regional economic growth and create local jobs by generating new jobs within the installation, maintenance, and energy-related sectors and services. For instance, reliable electricity can help new small enterprises get off the ground [75], use electric machinery to enhance farming practices [76], can even boost tourism by improving infrastructure in remote areas [77]. On the other hand, the distributed design of microgrids implies that energy is produced and used locally [78] hence reducing the loss of transmission [79] as well as increasing efficiency in the power system [80]. Indonesia's energy and economic growth will be helped by the fact that DC microgrids can be scaled up and last for a long time. If Indonesia smartly uses this technology, it could use its huge and green resources to meet its future energy needs, boost local economic growth, and reach its sustainability goals.

Meanwhile, DC microgrid implementation in Indonesia may help in employing local renewable energy sources, reducing energy loss for the residential users' community, thus minimizing environmental effects while promoting sustainable development [81]. By implementing DC microgrid, electricity will be so generated in higher level, closer to the point of its consumption, and eventually, this will lead to the decrease in deforestation and ecological effects. This would eventually result in a sustainable growth and in the knowledge level of community members about energy consumption including mitigation and adaptation to climate change. DC microgrids in Indonesia also will be able to decrease the emission of greenhouse gas, save nature, and be the electrification system of the future that is based on renewable energy. Replacement of fossil fuels with renewable technology is one of the primary applications of DC microgrids in Indonesia and particularly in rural and remote areas. In other words, DC microgrid implementation is accompanied by installation of infrastructure as well as regulations and policies which induce obstacles. Scalability in meeting the growing power demand, employment empowerment for local people as well as promoting Indonesia's green economy are some of the potential benefits that should be involved in the long-term plan of the country.

This study discusses the socio-economic and technology aspects associated with the implementation of microgrid system based on DC in Indonesia. It validates the work of Sulaeman *et al.* [2] and Nasir *et al.* [20] concerning remote microgrids scale and sustainability, and Zein *et al.* [1] regarding electrification rate with gray forecasting models. It further infers on the efficiency of renewable integration supplemented by other services by developing approbation from Werth *et al.* [6] and Iovine *et al.* [7] who look at the technology discussion. The study has its findings put in a universal perspective by examining the practical implications in Indonesia of the DC microgrid, one of the methods to ensure reliability in electricity supply that is crucial to the economic development [69], [71]. This study's distinctive views on the DC microgrid installation in Indonesia as well as its production from the other researches are discussed in this research that makes this research unique. This research is of socio-economic factors and policy frameworks used to show their role in DC microgrid viability in rural area of Indonesia where technical aspects of microgrids has been dominant in previous studies.

Furthermore, this study focused on how DC microgrids could be used in energy transition of Indonesia that is being influenced by the aspects of technology, economy, and policy. DC microgrids, in particular, are cost-competitive and eco-friendly, especially when connected to the surrounding renewable energy sources. The research established the fact that Indonesia's geographical and infrastructural diversity brings forth some unique challenges. Moreover, it was seen to that the use of microgrid could contribute socio-economic benefits. This research highlights that the applications of DC microgrids can enhance communities' socio-economic situation and the availability of energy in their remote areas. Hence, any future approaches should be aimed at the reinforcement of these systems fitted for Indonesia's specific island conditions which can then be set as a standard practice for similar issues in other parts of the world. The results highlight that the use of DC microgrids in rural and remote rural Indonesia can help enhance the energy resilience and sustainability.

4. CONCLUSION

This research critically assesses the potential opportunities and challenges of implementing DC microgrids in rural networks, particularly in Indonesia. This research is a step forward in DC microgrid implementation in Indonesia towards understanding from the existing literature and introducing new insights. Most of the previous research are more technical aspects dealing with the functional characteristics of DC microgrids. Hence, this work takes the different approach which aims to investigate the social and economic impacts and regulatory structures, thereby, uncovering a complex interaction of variables which determine the practicality of DC microgrids in Indonesia's specific rural environment. This multifaceted approach gives an original insight on the deployment of renewable energy sources, considering the opportunities and challenges of DC microgrid technology in Indonesia. The study makes it evident that specific government interventions and well-planned technological investments are the keys to reaching the goals of sustainable rural electrification and energy security. Hence, it creates an opportunity for further research and exploration in the areas where similar kind of issues arise.

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BIOGRAPHIES OF AUTHORS

Levin Halim completed his undergraduate studies in electrical power engineering and postgraduate study in electrical engineering from Bandung Institute of Technology in Indonesia in 2014 and 2015 respectively. Currently, he has the responsibilities as Assistant Professor in the Department of Electrical Engineering at Parahyangan Catholic University. The research area includes renewable energy, power quality, power electronics, power generation, power delivery, power supply quality, power transmission reliability, power transmission lines, power transmission planning, power transmission protection, battery chargers, circuit breakers, harmonic distortion, load flow control, power distribution protection, and the use of artificial intelligence in power systems. He can be contacted at email: halimlevin@unpar.ac.id.

Pinto Anugrah had got his B.Eng. in Engineering Physics and the M.Eng. degree in Energy Systems from Universitas Gadjah Mada, Yogyakarta, Indonesia awarded in 2014 and 2016. His research areas of interest include energy planning, energy modeling, and renewable energy. He can be contacted at email: pinto@eng.unand.ac.id.

Aditya Kurniawan pursued higher education at the prestigious University of Newcastle Upon Tyne in England, United Kingdom, where he earned a Postgraduate Diploma in Engineering with a specialization in Robot Vision and Artificial Intelligence. He further honed his skills with Certificates of Professional Expertise in Mechatronics from Höhere Technische Bundeslehr und Versuchsanstalt in St. Polten, and Festo Gesellschaft m.b.H. in Vienna, Austria. He has also accumulated significant project experience in the areas of Robot Vision, Human-Machine Interface (HMI), Artificial Intelligence (AI), and Internet of Things (IoT). This expertise was gained through his role as Chief Technological Officer (CTO) at PT Trilogi Global Services, a startup company operating in the technology, and automation sector. He can be contacted at email: aditya@akabi.ac.id.

Khairuddin Karim received the S.T. (bachelor of engineering) and M.T. (master of Engineering) degrees in electrical engineering from Hasanuddin University Ujung Pandang and Institut Teknologi Sepuluh November Surabaya, in 1994 and 2009, respectively. Currently, he is the Head of Electrical Engineering Department State Polytechnic of Samarinda. Field of his research interests include the applications of artificial intelligence, evolutionary and heuristic optimization techniques to power system planning, operation, and control. He can be contacted at email: khairuddin_karim@polnes.ac.id.