THE FUTURE OF POWER SEMICONDUCTOR DEVICES ROLE IN SMART GRID IMPLEMENTATION IN INDONESIA

MASA DEPAN PERAN DIVAIS SEMIKONDUKTOR DAYA PADA IMPLEMENTASI SMART GRID DI INDONESIA

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ABSTRACT

The use of power semiconductor devices as interfaces of distributed power generators in the smart grid is the key justification for the device advancement. It is the important forthcoming energy scheme for Indonesia to overcome the national electrical power shortage. The study of semiconductor devices focuses on their application in circuit breaker based on power semiconductor device, (solid-state circuit breaker/SSCB), which is a key element for the safety system in the smart grid scheme. An investigation on several devices in the market recommends a power semiconductor device type to be promoted in the near future for this specified application. The associated standardization infrastructure for the future of power device research, development and manufacturing in Indonesia is also presented. This paper presents the benefit of strengthening the role of power semiconductor devices in the electrical energy sector in Indonesia. It also shows that the IGCT will be the most promising device to be implemented in circuit breakers for transmission and distribution system.

Keywords: power semiconductor devices, circuit breaker, smart grid, distributed power generation

ABSTRAK

Peran divais semikonduktor daya sebagai antarmuka pembangkit daya terdistribusi dalam smart grid*, merupakan alasan dari pengembangan divais semikonduktor daya. Ini merupakan skema energi masa datang dalam mengatasi permasalahan kekurangan listrik di Indonesia. Kajian ini berfokus pada implementasi* circuit breaker *berbasis divais semikonduktor (SSCB) yang merupakan elemen keselamatan penting dalam sistem* smart grid. *Suatu investigasi terhadap divais yang telah beredar di pasar bebas menghasilkan rekomendasi jenis divais untuk dikembangkan pada masa yang akan datang. Juga dibahas infrastruktur standardisasi terkait dengan riset, pengembangan, dan produksi elektronika daya, di Indonesia. Makalah ini menggambarkan pentingnya penguatan peran divais semikonduktor daya sebagai bagian dalam bidang energi listrik di Indonesia. Makalah ini juga menggarisbawahi bahwa IGCT merupakan divais yang paling menjanjikan untuk diimplementasikan dalam* circuit breaker *untuk sistem transmisi dan distribusi.*

Kata Kunci: *divais semikonduktor daya, rangkaian pemutus arus,* smart grid, distributed power generation

1. INTRODUCTION

The introduction of smart grid into national power line is driven by the need for the provision of a better electrical energy supply. During its development, the new system must demonstrate evidence of quality, safety, and reliability to the stakeholders so that it can be widely accepted. Therefore, an accomplished standardization for the new technology is required not only for the new grid system itself, but also for all subsystems and elements.

General assumption is that the world energy consumption increases at the rate of 1.6% yearly up to 2020.[1] In this situation, Indonesia's energy consumption increased by 5.1% in 2013, much higher than in 2012 (0.5%), and well over its 10 year average (3.7%). The main energy sources that we have (oil, coal, natural gas and non-fossil fuel) yield the electrification ratio just by 75%. Therefore, breakthrough is needed to achieve electrification ratio target of 100% by the end of 2020.

The prospective energy source in the future is expected much more to come from the renewable sector.[2] Solar energy is the most potential renewable source which is regrettably yet unused. This huge opportunity of generating electricity from renewable sources can alleviate the renewable–sourced electricity. With the massive expected contribution from solar plants, the renewable electric generation can easily contribute more than 50% of the total generated electricity. Thus, distributed power generation, also known as distributed generation (DG), will be needed to support it.[3]

Recently in Indonesia, any developments in electrical energy are intended to deal with the country's energy shortage. Wheareas, originally, the main motivation for the development of the smart grid is the presence of new electrical generation schemes. Through years of development, the electrical power generation and distribution has transformed its pattern from a centralized to a distributed structure. DGs bring power generation closer to customers and have been shaped mostly in advanced technology countries such as United States of America, European countries, and Japan. In interconnecting DGs into a smart grid, the use of power semiconductor devices becomes a necessity, in the interest of power quality. Selecting prospective devices to promote in a particular field should be done carefully to avoid unnecessary investment.[4–6] Furthermore, a quality infrastructure for semiconductor devices and modules should also be established in supporting their development and manufacturing to meet every market requirement.

This paper provides an overview of the necessity of developing power semiconductor in Indonesia. The study reviews the benefit of smart grid system deployment especially in supporting distributed generations (DGs) attachment, in order to diversify electric power sources. The discussion of the DG incorporates its technical challenges in the provision of the reliable, the available, and the safety of DG-attached smart-grid system, where the use of solid-state circuit breaker as a safety system becomes imperative. For the future research and development direction, an investigation on power semiconductor devices is also conducted to find the best device for a particular circuit breaker application. Finally, this paper gives a view of power semiconductor device research, development, standardization infrastructure for the future power device, development and manufacturing, also the benefit of strengthening, and other stakeholder responsibilities in order to elevate the role of power semiconductor device in Indonesia.

2. THE SMART GRID

The smart grid concept combines a number of technologies, end-user solutions and addresses a number of policy and regulatory drivers and it does not have a single clear definition.[7] The European Technology Platform[8] defines smart grid as: "An electricity network that can intelligently integrate the actions of all users connected to it—generators, consumers and those that do both—in order to efficiently deliver sustainable, economic, and secure electricity supplies. According to the U.S. Department of Energy:[9] "A smart grid uses digital technology to improve reliability, security, and efficiency (both economic and energy) of the electric system from large generation, through the delivery systems to electricity consumers and a growing number of distributed-generation and storage resources". In *Smarter Grids: The Opportunity*,[10] the smart grid is defined as: "A smart grid uses sensing, embedded processing, and digital communications to enable the electricity grid to be observable (able to be measured and visualised), controllable (able to be manipulated and be optimised), automated (able to adapt and self-heal), and fully integrated (fully interoperable with existing systems and with the capacity to incorporate a diverse set of energy sources)". Therefore, the smart grid enables increasing demand response of distributes power generation; also known as distributed generation (DG). Active distribution networks is one of the early smart grid initiatives. Figure 1 is a schematic of a simple distribution network with DG and shows that interfaces are imperative in such network.

3. TECHNICAL CHALLENGES OF DG

Distributed power generation can have positive impacts on electricity distribution.[11–13] It can also improve distribution system reliability

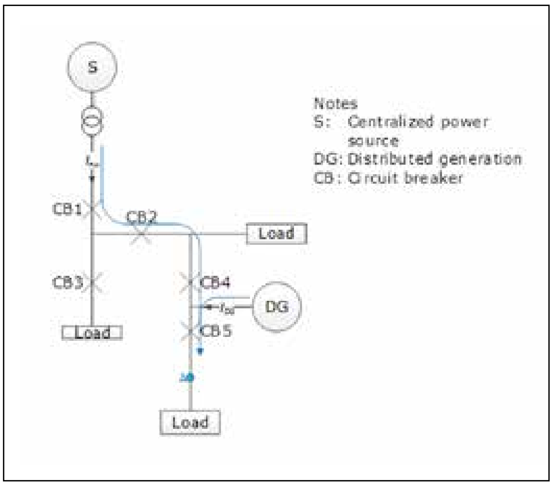

Figure 1. Distribution Network Active Management Scheme[7]

with backup generation capability, which serves customers when the main electric supply is interrupted. This kind of interruption (intended islanding) is an important feature of DG for a distribution line, which is geographically far from the main electric power supply. Unfortunately, attaching DGs into a power distribution network usually causes technical problems that can result in degradation of reliability.[14, 15] Reliability aspect, such as degree of a system or component to function under stated conditions or characteristics for a specified period of time, power quality, and the degree to which power characteristics align with the ideal sinusoidal voltage and current waveforms, could be compromised. Unfortunately, it is almost impossible to generate the ideal sinusoidal waveform without any distortion in real plants.

Availability, from customer's point of view, could refer to a power supply problem condition when electrical power is not properly supplied. This condition can be caused by a fluctuation of generated power.[11, 16] Some energy conversions—such as wind turbine, photovoltaic solar array, hydro turbine, and biogas engines—depend on their sources. This will result in fluctuations in the power supplied by a DG and the reliability problem will occur. DGs penetration in a distribution network, which is specified in an IEEE standard, need a fast-response system, which is included in the general requirements. In accordance with this requirement, service voltage deviations at other areas than the area of electric power system (EPS area) should be avoided. According to the standard, if a fault is detected in a circuit and removed by de-energizing the circuit, the DGs should stop energizing the particular area EPS.[17, 18]

The presence of a DG has an impact on short circuit levels of the distribution line to which it is attached and on the direction of current flow. Insufficient fault detection and protection devices do not only affect the performance of a DG, but also harmful by causing bi-directional power flow. This situation makes another scenario in which the DG could cause incoordination in protection when a fault condition occurs. In the case of both negative impacts of DGs, the presence of circuit breaker is imperative. However, the rating of existing circuit breakers places an upper limit on the range of the new fault levels (including DG contributions) that can be permitted in a particular part of the network.[19]

4. CIRCUIT BREAKERS

Circuit breakers are critical parts in smart grids as well as in the other power transmission and distribution systems. They exist because of their ability in handling some safety hazards that can possibly disturb the safety condition of the system operation.[20, 21] Two conditions that a circuit breaker deals with are current overload and short circuit current. Dealing with these two events, a circuit breaker must be able to interrupt an excessive current as soon as it is detected to avoid a hazardous overcurrent level.

Circuit breakers, basically, work on three principles (Figure 2): sense the observable current; decide whether it is an overcurrent; and act to interrupt the current. The first successfully developed circuit breaker was the mechanical circuit breaker (MCB) and the later development is the solid-state circuit breaker (SSCB). MCB is distinguished from SSCB by the trip mechanism of the breaker, SSCB employs power semiconductor devices as the switch for the trip mechanism.

SSCB are the best candidates for this system, free from arc and having fast response

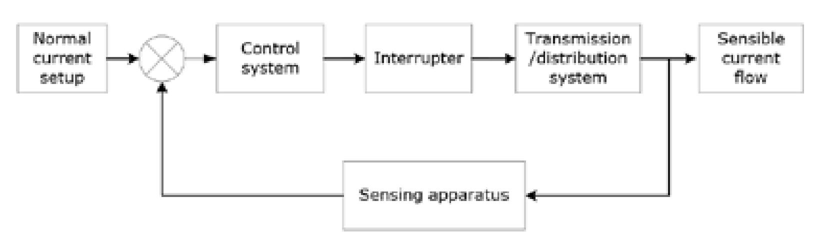

Figure 2. Circuit Breaker Working Principle

compared to MBCs due to the energy transformation from electrical to mechanical work. However, power semiconductor devices also introduce other problems in a circuit breaker. Therefore, SSCB should have protections against the presence of overvoltage and excessive energy storage. In this case, protection circuits such as snubbers and varistors are essential, both to protect SSCB from an overvoltage and to absorb the excessive energy with a trade-off between each other. Any controllable power semiconductor device, basically, could be used in an SSCB system. Referring to Figure 2, devices, such as MOSFET and IGBT from the transistor family, GTO and IGCT from the thyristor family, can be used as a switch in an SSCB.[22–24] Nevertheless, further study should be addressed to find an optimum power semiconductor device to use in a system.

5. POWER SEMICONDUCTOR DEVICES AS SSCB COMPONENT

Power semiconductor devices, especially the high-power ones, have an important contribution in improving power supply reliability, the use of energy storage systems, flexible AC or DC, transmission systems, and distributed generation. However, along with the increase of power transmission and distribution requirements, especially in a smart grid where DGs are involved, there are some challenges that a power semiconductor device has to face: component packaging and cooling methods, reliability of the higher-power handling requirement, and cost of the device implementation.

The power-device based DG interface could provide some benefit to local power reliability. If a DG system is being used as a back up power, an apparatus must be able to switch from connecting to the grid to the stand-alone mode. This could be an issue for non-power semiconductor devices because traditional circuit breakers with a switching range from 20 to 100 ms (more than 1 cycle) may be too slow to keep the sensitive load operating. On the contrary, power-semiconductor-device based breakers, could allow the smart grid systems to transfer loads from the grid to the DG source without powerless period.[25, 26]

The power-device based interface could minimize the fault current contributed by DGs. The increase of DG technologies penetration in power distribution systems makes the more acute negative effects on the available fault current, the coordination, and the protection schemes. SSCB applications have a high possibility in simplifying the attachment of grid-connected DG, while also minimizing their negative impacts. The concept of solid-state breakers is relatively simple: replacing the static and movable electrode contacts of the traditional breaker (vacuum, SF6, air, oil, etc.). The speed of even the slowest semiconductor switch orders of magnitude is faster than traditional technologies. Moreover, this interface could also enable the integration of more than one DG system. The use of a DC bus, that allows the integration of several inverters into one larger inverter that would be common to several DG technologies, serves for an integration of several types of DG technologies at a common point.[27]

Power semiconductor devices, in general, have a benefit from their modularity that allows designers to arrange modules to meet a specified requirement, optimize a specific device for a given application, and minimize the size, cost and complexity of the power-device based DG interface. The approach could directly provide a better solution for the specific application. However, this approach narrows the market opportunity for such a device and excludes it from the benefit of larger scale production. BJTs are controllable power semiconductor devices that are not a suitable choice for SSCB. The MOSFET has a higher switching speed than that of IGBT even though the latter still has a high switching speed if compared to any MCB. In terms of voltage capability, later developed IGBTs (up to 6.5 kV) offer a higher voltage rating, compared to MOSFETs, so that they are more suitable to apply in a circuit breaker application.

IGCTs are the most appropriate power semiconductor device for SSCB, especially at a high-current handling requirement. A thyristor based semiconductor devices, the IGCT, is in fact a combination of the gate turn-off (GTO) concept and an integrated gate-drive circuit. From the GTO, this device adopts the advantages of high voltage and current handling capabilities, high surge current capability, and very good electrical ruggedness. This device also exhibits a superior on-state voltage drop, compared to an IGBT. The high turn-off time of IGCT is not really a problem since it is still much faster than any MCBs.

With various types of devices available in the market, the appropriate device has to be selected carefully as well as following all technical specifications inherent to a circuit breaker. Device characteristics, such as maximum ratings, on and off-state characteristics, which can be obtained from the manufacturer's data sheets and application notes, should be examined wisely to meet the circuit breaker requirements, and these requirements could be different for every need.

Circuit breaker requirement assumptions, derived from discussions with a power company, considered in the selection of the proper SSCB device are: the maximum transient current flow through device(s) is 3 kA, while normal condition is 500 A, the maximum transient voltage across device(s) is 16 kV with a continuous voltage of 10 kV and the devices will be series connected with diodes for accommodating reverse blocking voltage. An illustration of the architecture of power semiconductor device in an SSCB is shown in Figure 3.

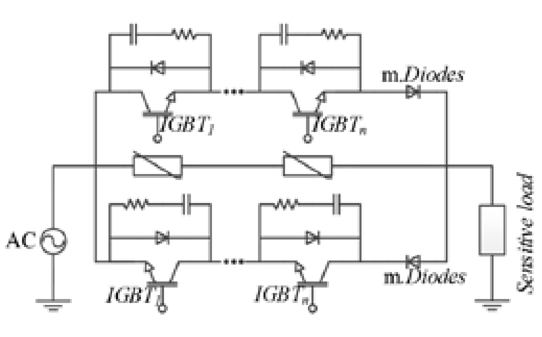

Figure 3. An Illustration of an SSCB Architecture (Using IGBT for the Device Portrayal)

The first circuit breaker requirement to consider should be the short circuit current which dictates the IGBT's capability during the occurrence of a short circuit. It corresponds to the I_{SC} (for IGBT) and the I_{TGQM} (for the thyristor device). The next two characteristics are intended to sort potential devices due to their efficiency.

Once a device is in conformity with the I_{SC} requirement, investigating its maximum blocking voltage (V_B) ratings becomes imperative. The V_B rating could be found as V_{CES} for IGBTs or V_{DRM} for the thyristor devices. The blocking voltage characteristics dictate the number of devices needed in the designed circuit. The lower the blocking voltage, the more devices are necessary in supporting the maximum voltage desired (V_{max}) of 16 kV. The number of devices (n) needed is calculated by $n = \frac{V_{max}}{V_B}$. An additional extra device could be added for the backup purpose in anticipating a potential device failure.

The next characteristic to take into account is the conduction losses of the device. Calculation of a single device conduction loss (P_{Loss}) uses

$$P_{Loss} = \frac{1}{T}\int_0^T \left[V_{AC}\left(I_C\right)\times I_C\left(t\right)\right]dt \qquad ....(1)$$

where $V_{AC}(I_C)$ is anode-cathode voltage as a function of cathode current with T = 20 ms, the sinusoidal waveform period. The relation of $V_{AC}(I_C)$ provided by the manufacturer in the 125°C on-state characteristics. The $I_C(t)$ is defined as

$$P_{Loss} = \frac{1}{T}\int_0^T \left[V_{AC}\left(I_C\right) \times I_C\left(t\right)\right] dt$$

$$I_C\left(t\right) = \begin{cases} \alpha \sin\left(2\pi ft\right), \ 0 \le t \le \dfrac{1}{2f}, \\ 0, \quad \dfrac{1}{2f} \le t \le \dfrac{1}{f} \end{cases} \qquad \text{.... (2)}$$

with a = 500 A and f = 50 Hz, the peak current and frequency, respectively, of the current which assumed to have a half-wave sinusoidal waveform.

The number of devices needed is ruled by blocking voltage. The lower the power loss, the less energy required by the cooling system to remove heat from the circuit in order to maintain safe operational temperature. Since the number of devices (n) only serve a half waveform, the total three-phase power loss is calculated as $3P\,P_{Loss} = 6 \times n \times P_{Loss}$.

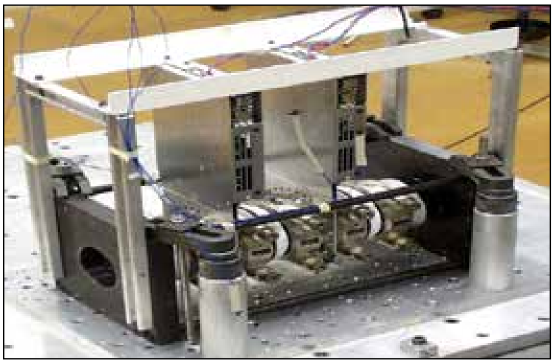

Figure 4. Representative Illustration of an IGCT-based SSCB Mechanical Assembly (Only Power Devices and Heat-sinks, No Snubbers)

Lastly, an additional consideration in the device selection could be focused on the package type. Press-pack construction makes devices easier to be series connected and able to perform conduction during failure state, which is suitable for circuit breakers (Figure 4).

Table 1 shows the list of potential devices as SSCB component. Further research and development of device structure should overcome the blocking voltage and power loss problems, especially for the IGCT and IGBT device with the purpose to widen the device choice. Regarding the packaging type, except for the two standard housing IGBTs, the rest of devices listed in Table 1 are in presspack type. Regrettably, the best candidate from transistor family come in the standard housing packaging. Therefore, it is another task of packaging research to increase the efficiency of press-pack type.

The list in Table 1 also includes a symmetric GTO. The interesting feature of this symmetric device is that it does not need series connected diode in supporting blocking voltage. The total power loss (3 phase P_{loss}) characteristics in the list are in regard of power device only, excludes the diode. Therefore, when diodes power loss

Table 1. Characteristics for Device Selection

No.	Type	Note	V_B	I_{max}	n	1 Device P_{Loss} (W)	Total 3phase P_{Loss} (W)
1.	GTO-1	Asymmetric-GTO	4,500	4,000	5	174	5,220
2.	IGCT	Asymmetric -IGCT	6,500	3,800	4	269	6,456
3.	GTO-2	Asymmetric -GTO	4,500	3,000	5	261	7,830
4.	GTO-3	Asymmetric -GTO	6,000	3,000	4	328	7,872
5.	IGBT-1	Standard housing	6,500	3,400	4	352	8,448
6.	IGBT-2	Standard housing	4,500	3,500	5	303	9,090
7.	IGBT-5	Press-Pack	4,500	3,150	5	317	9,510
8.	IGBT-6	Press-Pack	4,500	3,400	5	324	9,720
9.	IGBT-3	Standard housing	6,500	3,000	4	434	10,416
10.	GTO-4	Asymmetric -GTO	4,500	3,000	5	395	11,850
11.	IGBT-4	Standard housing	6,500	3,000	4	629	15,096
12.	GTO-5	Symmetric-GTO	6,500	1,500	4	756	18,144

is included, the total power loss could be compromised.

6. A VIEW OF POWER DEVICE RESEARCH AND DEVELOPMENT

It is obvious that the use of a smart grid with all of its gears will benefit the Indonesian power sector. However, the wide variety of component to build a smart grid up should be carefully considered. The easiest way in resolving electrification issues in Indonesia is to adopt entire technologies from abroad, including power generation, semiconductor material research, power transmission, appliances energy efficiency, etc. However, adopting all technologies from abroad will increase Indonesia's energy vulnerability in spite of solving the problem. This problem could be overcome by establishing research and development facilities. Due to the broad scope of sciences and engineering fields in implementing the smart grid system, massive investments and strong policy should be established to support the manufacturer.[28, 29]

The electrification of 2,342 inhabited islands in Indonesia[30] and the desire to become an advanced country demand the Indonesian advanced electrical management. Regrettably, the 35,000 MW initiative launched by the government exclude the DG-attached smart-grid program. Hence, the development of power semiconductor devices, for this particular application, will not be a priority, at least until 2019. Since the power semiconductor device is a potential component for interfaces in the transmission and distribution of electrical power,[25, 26, 31] research on this particular device should be enhanced for the future national energy policy. Nevertheless, the research field should be carefully selected.[32, 33]

Power semiconductor research and engineering is a broad multidisciplinary study, which is spread from applied nanotechnology in device structure research, module engineering, up to the engineering of device application in practical use such as for the SSCB. Recently, the research in material is still exploring any possible material to compare to regular silicon. GaN and SiC are still the two most attractive materials.[34–36] In the packaging research field, improving device inductance and reliability in high temperature are the main issue, as well as providing IGBT with reverse conducting ability and IGCT with reverse blocking capability.[37–39] In the application field, research are exploring and enhancing the performance of power semiconductor devices in any application, such as transformer and circuit breaker.[31, 35, 40] However, the investigation of published papers in Google Scholar shows that research in Indonesia, which are associated with power semiconductor devices, mainly discusses the application aspect of the devices.

It is logical that promoting power semiconductor research in Indonesia starts from its application to provide for the market needs. In order to satisfy the market, to accelerate their industrialization, and to ensure customer satisfaction, any research products should be standardized. Therefore, a series of standardization efforts should also be addressed. Since the electrical provision in a smart grid system depends on its availability, all parts that builds the system should be safe in terms of being reliable and maintainable.

Standardization is the slightest attempt in ensuring system and all its element meet their minimum safety requirements. Minimal requirements for the safety of the smart grid and all of its elements should be formed. The requirements that are standardized should also consider Indonesian national differences. Regrettably, nowadays there are only a few harmonized standards in Indonesia for electrical components. From 705 Indonesia National Standard (SNI) on electrical products, less than ten standards are about the power semiconductor devices.[41]

Efforts in the standardization is a key point in supporting national industry which should be accompanied by establishing strong conformity assessment agencies and other quality infrastructures. The role in these standardization efforts should be offered by the government to show a good will in order to attract local and foreign investments. Nevertheless, the research, industries, and government stakeholders should share the responsibilities and should be in best coordination in order to the power semiconductor device has a bright future for the use in electrical power transmission and distribution.

7. CONCLUSION

Throughout the description and the discussion, employing renewable energy resources as distributed generation to increase electrical power generation could contribute in solving the national electrical power shortage problem. Introducing the DGs into the existing centralized grid means to replace the grid by the smart grid scheme where the use of power semiconductor devices is compulsory. Therefore, the need for the devices will increase tremendously, especially for the IGCT-type device, so it is understandable that Indonesia could be a bright market for power semiconductor devices. The research and development of the devices, should be directed carefully so that it could be a well-meaning investment, particularly, in strengthening the electrical power provision by reducing its dependence on imported components and start to develop the infrastructure to support the idea of renewable energy in Indonesia.

8. REFERENCES

[1] Dewan Energi Nasional Republik Indonesia. 2014. *Outlook Energi Indonesia 2014.* Dewan Energi Nasional Republik Indonesia.

[2] Pusat Data dan Teknologi Informasi Energi dan Sumber Daya Mineral Kementerian Energi dan Sumber Daya Mineral. 2013. *Kajian Supply Demand Energi*. Pusat Data dan Teknologi Informasi Energi dan Sumber Daya Mineral Kementerian Energi dan Sumber Daya Mineral.

[3] Pearce, J. M. 2009. "Expanding Photovoltaic Penetration with Residential Distributed Generation from Hybrid Solar Photovoltaic and Combined Heat and Power Systems". *Energy* 34 (11): 1947–1954.

[4] Ackermann, T., G. Andersson, and L. Söder. 2001. "Distributed Generation: A Definition". *Electric Power Systems Research* 57 (3): 195–204.

[5] Charles Jr, H. K., and N. Sinnadurai. 2008. "Electronics, Energy and the Environment". In *Electronics System-Integration Technology Conference. ESTC 2008. 2nd.* IEEE.

[6] An Luo, Qianming Xu, Fujun M.A., and Yandong Chen. 2016. "Overview of Power Quality Analysis and Control Technology for the Smart Grid". *Journal of Modern Power Systems and Clean Energy* 4 (1): 1–9.

[7] Ekanayake, J., N. Jenkins, K. Liyanage, and J. Wu. 2012. *Smart Grid: Technology and Applications*. John Wiley & Sons.

[8] EU Directorate-General for Research Sustainable Energy Systems. 2006. *European Smart Grids Technology Platform: Vision and Strategy for Europe's Electricity Networks of the Future*. EU Directorate-General for Research Sustainable Energy Systems.

[9] U.S. Department of Energy. 2009. *Smart Grid System Report*. U.S. Department of Energy.

[10] UK Department of Energy and Climate Change. 2009. *Smarter Grids: The Opportunity*. UK Department of Energy and Climate Change.

[11] Hu, J., J. Zhu, dan G. Platt. 2011. "Smart Grid—the Next Generation Electricity Grid with Power Flow Optimization and High Power Quality". In *2011 International Conference on Electrical Machines and Systems (ICEMS)*. IEEE.

[12] Fang, Xi, Satyajayanti Misra, Guoliang Xue, dan Dejun Yang. 2012. "Smart Grid—The New and Improved Power Grid: A Survey". *IEEE Communications Surveys & Tutorials* 14 (4): 944–980.

[13] Soroudi, A. 2012. "Possibilistic-Scenario Model for DG Impact Assessment on Distribution Networks in an Uncertain Environment". *IEEE Transactions on Power Systems* 27 (3): 1283–1293.

[14] Mägi, M. 2012. "Analysis of Distribution Substation Topologies for Energy Exchanging between EV and Utility Networks". In *11th International Symposium "Topical Problems in the Field of Electrical and Power Engineering" Pärnu*.

[15] Nikkhajoei, H., and R. H. Lasseter. 2007. "Microgrid Protection". In *2007 IEEE Power Engineering Society General Meeting.* IEEE.

[16] Putrus, G.A., Pasist Suwanapingkarl, David Johnston, E. C. Bentley, dan Mahinsasa Narayana. 2009. "Impact of Electric Vehicles on Power Distribution Networks". In *2009 IEEE Vehicle Power and Propulsion Conference*. IEEE.

[17] *IEEE Application Guide for IEEE Std 1547(TM), IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems.* IEEE Std 1547.2-2008, 2009: 1–217.

[18] IEEE. 2003. *IEEE 1547* in *Standard for Interconnecting Distributed Resources with Electric Power Systems*. IEEE.

[19] Cornforth, D., S. Sayeef, and T. Moore. 2011. "Beyond Overcurrent Protection: Distributed Generation in the Future Grid". In *Innovative Smart Grid Technologies Asia (ISGT), 2011 IEEE PES*. IEEE.

[20] Rekola, J. 2012. *DC Distribution and Power Electronics Applications in Smart Grid*. 2012.

[21] Meyer, C., S. Schroder, and R. W. De Doncker. 2004. "Solid-State Circuit Breakers and Current Limiters for Medium-voltage Systems Having Distributed Power Systems". *IEEE Transactions on Power Electronics* 19 (5): 1333–1340.

[22] Conti, S. 2009. "Analysis of Distribution Network Protection Issues in Presence of Dispersed Generation". *Electric Power Systems Research* 79 (1): 49–56.

[23] Magnusson, Jesper, Robert Saers, Lars Liljestrand, and Goran Engdahl. 2014. "Separation of the Energy Absorption and Overvoltage Protection in Solid-State Breakers by the Use of Parallel Varistors". *IEEE Transactions on Power Electronics* 29 (6): 2715–2722.

[24] Shammas, Noel Y.A. 2005. "The Role of Semiconductor Devices in High Power Circuit Breaker Applications". *WSEAS Transactions on Circuit and Systems* 4 (7): 826.

[25] Blaabjerg, F., Z. Chen, and S. B. Kjaer. 2004. "Power Electronics as Efficient Interface in Dispersed Power Generation Systems". *IEEE Transactions on Power Electronics* 19 (5): 1184–1194.

[26] Carrasco, Juan Manuel, Leopoldo Garcia Franquelo, Jan T. Bialasiewicz, Eduardo Galván, Ramón Carlos PortilloGuisado, … and Narciso Moreno-Alfonso. 2006. "Power-Electronic Systems for the Grid Integration of Renewable Energy Sources: A Survey". *IEEE Transactions on Industrial Electronics* 53 (4) : 1002–1016.

[27] Kroposki, Benjamin, Christoper Pink, R. Deblasio, dan P.K. Sen. 2010. Benefits of Power Electronic Interfaces for Distributed Energy Systems. *IEEE Transactions on Energy Conversion* 25 (3) : 901–908.

[28] Gungor, Vehbi C., Bin Lu, and Gerhard P. Hancke. 2010. "Opportunities and Challenges of Wireless Sensor Networks in Smart Grid". IEEE Transactions on Industrial Electronics 57 (10): 3557–3564.

[29] Gungor, Vehbi C., Dilan Sahin, Taskin Kocak, dan Gerhard P. Hancke. 2011. *Smart Grid Technologies: Communication Technologies and Standards. IEEE transactions on Industrial informatics* 7 (4) 529–539.

[30] *15.337 Pulau (87%) di Indonesia Tak Berpenghuni*. 2013. kominfonewscenter.com., accessed on September 30, 2016.

[31] Kolar, J. W., and G. Ortiz. 2014. "Solid-State-Transformers: Key Components of Future Traction and Smart Grid Systems". In *Proc. of the International Power Electronics Conference (IPEC), Hiroshima, Japan*.

[32] Mei, S., and L. Chen. 2012. "Research Focuses and Advanced Technologies of Smart Grid in Recent Years". *Chinese Science Bulletin* 57 (22): 2879–2886.

[33] Brunekreeft, Gert, Marius Buchmann, Christian Dänekas, dan Nils Vogel. 2015. "Regulatory Pathways for Smart Grid Development in China". In *Regulatory Pathways for Smart Grid Development in China*. Springer.,: pp. 119–138.

[34] Hirose, T., D. Mori, and Y. Terao. 2016. "Atomic Level Analysis of SiC Devices Using Numerical Simulation". *Simulation Technologies for Product Development* 62 (1): 23.

[35] Martinez, Wilmar, Masayoshi Yamamoto, Jun Imaoka, Freddy Velandia, dan Camilo A. cortes. 2016. "Efficiency Optimization of a Two-phase Interleaved Boost DC-DC Converter for Electric Vehicle Applications. In *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*. IEEE.

[36] Wu, Rui, JiaLiang Wen, Kunshan Yu, dan Dongyuan Zhao. 2012. "A Discussion of SiC Prospects in Next Electrical Grid". In *2012 Asia-Pacific Power and Energy Engineering Conference*. IEEE.

[37] Kozak, J. P. 2016. *Electro-Thermal Effects of Power Transistors on Converter Performance.* University of Pittsburgh.

[38] Yoshida, S., S. Noguchi, and K. Mukai. 2015. "RC-IGBT for Automotive Applications". *Power Semiconductors Contributing in Energy Management* 61 (4): 263.

[39] Vemulapati, Umamaheswara, Martin Arnold, Munaf Rahimo, Antonello Antoniazzi, dan Davide Pessina. 2015. "Reverse Blocking IGCT Optimised for 1 kV DC Bi-directional Solid-state Circuit Breaker". *IET Power Electronics* 8 (12): 2308–2314.

[40] Waldron, J. 2016. *Low-loss, Fast-acting Solid State AC/DC Breaker.* PCIM Asia.

[41] *Ketersediaan SNI Terkait 12 Sektor Prioritas Masyarakat Ekonomi ASEAN (MEA)*. 2016. PUSIDO-BSN.