FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 7 No. 3, June (Special Issue), 2023, pp 330 - 335
DOI: https://doi.org/10.33003/fjs-2023-0703-1965

SOLID STATE TRANSFORMER (SST) AND THE CHALLENGES OF THE FUTURE GRID

***[1]Nasiru B. Kadandani, [2,3]Sahalu Hassan, [1]Isiyaku Abubakar**

[1]Department of Electrical Engineering, Bayero University, PMB 3011, Kano, Nigeria
[2]School of Science and Engineering, University of Glasgow, G12 8QQ, University Avenue, Glasgow, United Kingdom
[3]Umaru Musa Yar'Adua University, PMB 2218, Katsina, Nigeria

*Corresponding authors' email: nbkadandani.ele@buk.edu.ng

ABSTRACT

Power flow management in both transmission and distribution grid networks is continuously being challenged by increased integration of distributed generations that are stochastic and intermittent in nature. This paper investigates the anticipated roles or functionalities required from solid state transformer (SST) to enable it address the challenges faced by the grid network. The SST is a power electronics based transformer build with flexibilities and intelligence required for performing ancillary services to the grid. The paper shows that, with the aid of SST, smooth integration of renewable energy sources and other functionalities such as power factor correction, reactive power compensation, harmonics mitigation, fault ride through and or fault isolation can be achieved in the future grid.

Keywords: Solid State Transformer, Line Frequency Transformer, Flexible Alternating Current Transmission System, Static Synchronous Compensator, Grid

INTRODUCTION

The traditional line frequency transformer (LFT) have for long being used to perform voltage transformation in alternating current (AC) transmission and distribution systems. This functionality has been considered satisfactory for a conventional grid that is static in nature. However, when the need of additional functionalities arise in such kind of static grid, the LFT has to be supported with additional circuitries to enable it deliver the required functionalities diligently. As an example, performing power factor correction or voltage profile improvement in the conventional grid equipped with LFT requires the support of a flexible alternating current transmission system (FACTS) device such as static synchronous compensator (STATCOM) (Kadandani & Maiwada, 2015b). Advancements in electrical power generation, transmission, distribution and consumption are continuously making the grid complex. For instance, large penetration of renewable resources into the grid, charging of electric vehicle (EV), connection of other non-linear loads and other new inventions are constantly changing the dynamics of the grid. These complexities necessitate the need of a smart transformer that can mimic the LFT in terms of voltage transformation and render additional functionalities to the system. To this extent, a smart device in the form of solid state transformer (SST) is being considered as a promising alternative.

The SST as an emerging technology is build with flexibilities and communication networks required for rendering additional services to the system. As such, with the aid of SST, important functionalities such as power factor improvement, reactive power compensation, harmonics mitigation, fault ride through and or fault isolation can be achieved in the grid network.

The concept of SST was first proposed in (McMurray, 1971) while the details of its circuit configurations was presented in (Kadandani et al., 2019). As the technology matured, the device has been considered in many applications. The work presented in (Gao et al., 2016; Gao et al., 2017; She et al., 2012) have considered the use of SST in grid integration of wind farms. In another development, the work presented in (Zhao et al., 2014; Steiner & Reinold, 2007) has taken the advantage of reduced footprint of SST to be considered for traction and other locomotive applications. The SST has also being considered in extreme fast charging of electric vehicles (Nair & Fernandes, 2021; Pool-Mazun et al., 2020), medium voltage applications (Zheng et al., 2021; Dong et al., 2019; Huang, 2016; & Lai, 2005), in the distribution system (Huber & Kolar, 2019; Montoya et al., 2015; Qu et al., 2019; Rehman & Ashraf, 2019) as well as in smart grid (She & Huang, 2013; She et al., 2014; Wang et al., 2009).

This paper investigates how the SST can be used to support the future power grid to cater for the challenges associated with the daily complications arising from large proliferation of renewable generation and connection of electric vehicles among others.

The Concept Of Solid State Transformer (SST)

General Overview of SST

As depicted in Figure 1a, SST is a smart transformer capable of transforming AC voltage at line frequency level into a high frequency one which is further stepped up or stepped down by a high frequency transformer (HFT) accompanied by a significant reduction in footprint which is then transformed back into the line frequency voltage level to feed some loads. Figure 1b shows the converter configuration of SST in a more illustrative manner. It consists of a rectifier, a DC-DC converter with a HFT and an inverter.

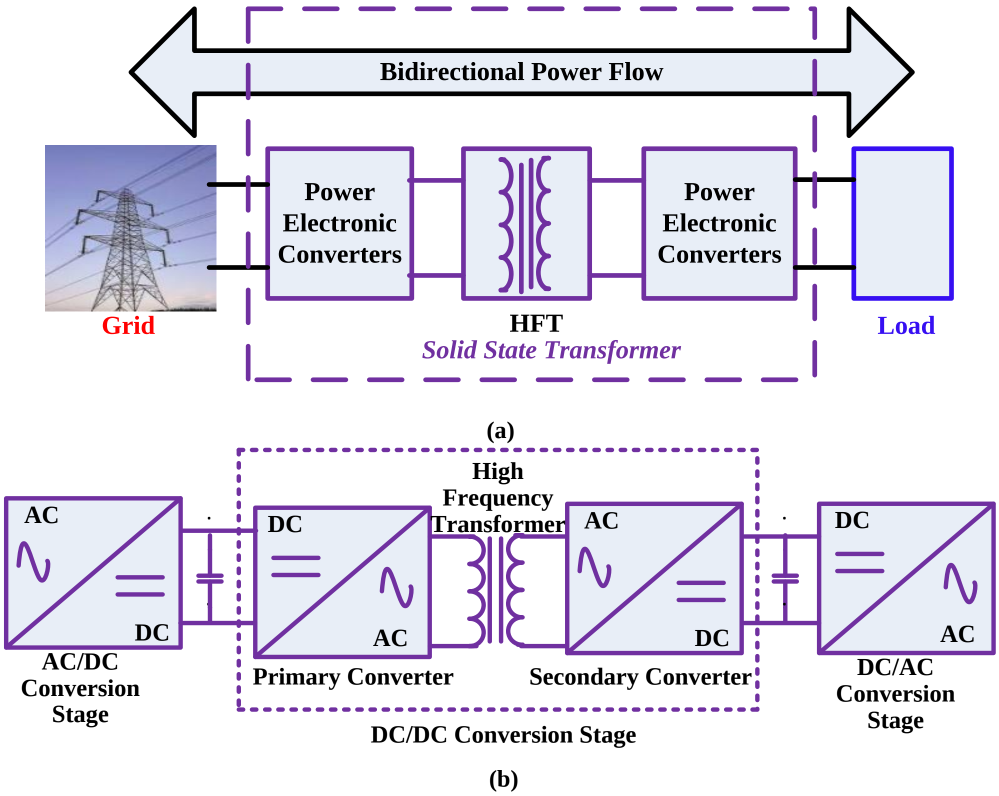

Figure 1: The SST System, **(a)** Block Diagram, **(b)** Converter Configurations

Basic Structures of SST

Figure 2 shows four possible circuit topologies of SST; namely single stage topology as depicted in Figure 2a, two stage topology with DC link on the low voltage side as depicted in Figure 2b, two stage topology with DC link on the high voltage side as depicted in Figure 2c, and three stage topology with DC links on both low and high voltage sides as depicted in Figure 2c. Selection of a particular topology is based on the type of applications and the functionalities required.

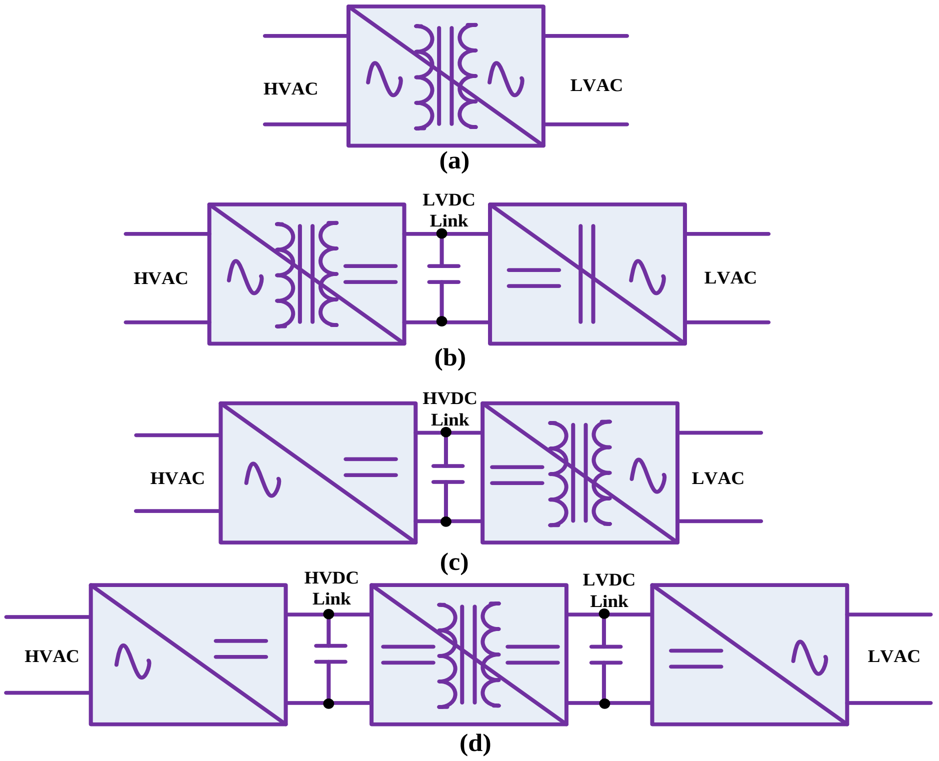

Figure 2: SST Topologies, **(a)** Single-Stage Topology, **(b)** Two-Stage Topology with LVDC Link, **(c)** Two-Stage Topology with HVDC Link, **(c)** Three-Stage Topology with LVDC and HVDC Links

Control Techniques of SST

Figure 3 depicts a classical control technique for SST. The strategy consists of two control techniques working together. The first is a power balance controller for the rectifier which is meant to regulate the flow of power between the rectifier and the DC-DC converter and also to regulate the high voltage direct current (HVDC) link. The second controller is called phase shift controller. Its function is to provide and control the required phase shift angle in the DC-DC converter and also to regulate the low voltage direct current (LVDC) link.

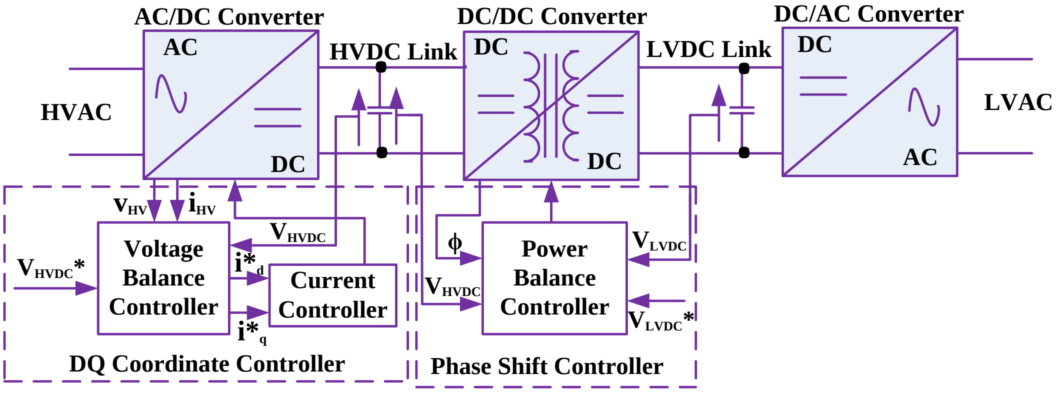

Figure 3: Block Diagram of SST Control Technique

Anticipated Functionalities of SST

In order to address all the challenges being faced by the grid network, the SST is expected to provide the following functionalities diligently and faithfully.

Self-Healing Transformation

With the presence of DC links on both LV and HV sides, SST can isolate a faulty section from the healthy part of the power network. To this extent, the regulated AC voltage at the receiving end of the system will not be distressed by the impact of voltage dip and or voltage rise at the sending end of the system (She & Huang, 2013). As such, the system is full aware of its operation status, thus guaranteeing real time monitoring. This capability makes the system self-healing in nature.

Resiliency to Disturbance and Threats

With the aid of proper sensing and communication network, the SST can make the grid resilient to transients and other disturbances from either the sending or receiving end. In the same manner, the system will be aware of possible natural disasters and appropriate precationary measures be taken accordingly. The sensors can also detect cyber attack and counter acts it accordingly.

Provision of Power Quality

Unlike conventional LFT, the SST doesn't need additional circuitries for power factor correction and or reactive power compensation. As such, the power output of SST is of high quality compared to that of the conventional LFT. With this capability, the SST can quickly tackle any transient disturbance and other power quality issues (Kadandani & Abubakar, 2023).

Promoting the Use of Renewable Generation

The conventional LFT used in most of the the existing utility grids are not fully compatible with the large proliferation of renewable generation into the grid. Fortunately however, the SST can tackle the transient and intermittent nature of renewable generation. The DC links and other power electronics component of the SST permits smooth incorporation of distributed generation into the grid.

Enabling Two-Way Communication

SST provides bidirectional power flow, thus enabling two-way communication at different levels of the grid. This feature is not available with the conventional LFT.

Asset Optimization

The SST can easily be eqipped with other emerging technologies that can make the grid optimize its assets. This can be achieved by proper monitoring and communication networks. As such, time-based maintenance can be achieved against the conventional condition-based maintenance.

Harmonic Mitigation

The availability of two DC links on SST allows it to decouple AC harmonics from the two sides. As such, the instantaneous power on the high voltage side may not be equal to that of the low voltage side (Huang, 2016). The harmonic components on either side of the SST can be attenuated with the aid of appropriate controller.

Voltage Sag Mitigation

In conventional power system, voltage sag mitigation is achieved by FACTS devices (Kadandani & Maiwada, 2015a). A typical FACTS controller that mitgates voltage sag is dynamic voltage restorer (DVR). However, the SST has in-build capability of mitigating voltage sag without the need of any FACTS controller.

Short Circuit Protection

SST can be incorporated with appropriate control techniques dedidcated for the interruption of fault and limiting the magnitude of short circuit current easily (She et al., 2013). With this capability, the SST may not need any additional circuity such as STATCOM used alongside with the conventional LFT for achieving the same functionality.

DC Connectivity

The design of SST with DC links on both sides of the device makes it easier for the device to connect with DC microgrid or DC loads.

Energy Routing

SST is fitted with sensors and communication facilities for the routing of electricity (Hambridge et al., 2015). The increased penetration of distributed generations into the grid requires a proper management of the demand and supply for the system. The SST as an energy router can be used to manage the demand and supply diligently (Hannan et al., 2020).

Energy Information Dissemination

SST is a smart transformer and when equipped with sensors, the device can desseminate energy information diligently and in secured manner free from any form of threat. Proper control algorithms regulate the power flow between the power electronics converters and provide bidirectional power flow capability.

Prevention of Blackout

With the aid of fast load reduction scheme, SST can be used to prevent blackout in the power system.

Flexibility and Intelligence

SST has a lot of flexibilities in terms of control techniques. It provides galvanic isolation and can decouple one side from the other thereby preventing propagation of faults from one side to another.

System Reliability Enhancement

SST is capable of improving the reliabilty of the grid network with the aid of its functionalities such as mitigation of power quality issues, fault ride through capability, power factor correction and or reactive power compensation. These functionalities may not require any other circuitries, but are rather inbuilt in the SST system.

System Compactness and Footprint

Apart from mimicking the conventional LFT in transforming system voltage from one level to another, the SST also provides the system with compactness and reduction in footprint. This is possible with the aid of HFT within the SST system. Thus, a compact system is easier to install and maintain. The reduction in the footprint will minimize transportation and installation cost.

Other Applications of SST

SST has already been committed to other applications and functionalities within and outside the grid network. Some of these applications are briefly presented in the following sub-sections.

Microgrid and Smart Grid Applications

Researchers have considered the use of SST in microgrid (Das & Kumar, 2017; Sun et al., 2022; Wang et al., 2016) and in smart grid applications (Kadandani, Dahidah, & Ethni, 2021b; Londero et al., 2019) for providing all the intelligence and flexibilities required for bidirectional power flow, sensing, communication and fault ride through capabilities required by the smart grid.

Charging of Electric Vehicles

SST has been considered as a promising device for charging of electric vehicles (Eshkevari et al., 2020; Tahir et al., 2021). The SST is being considered in this application because of its reduced size, and free from green house emission, making it environmentally friendly.

Traction and Other Locomotive Systems

The conventional LFT used in traction and other locomotive systems are bulky, thus reducing the efficieny of the systems. To cater for this, a lighter device such as SST is being considered as a possible option in such applications for efficiency improvement. Thus, when used in traction and other locomotives, the SST would provide voltage transformation, a compact and efficient system with other ancillary functionalities such as flexibility in terms of control techniques, intelligence and communication capabilities. The work presented in (Dujic et al., 2013; Ronanki & Williamson, 2018) have demonstrated the use of SST in traction systems.

Solar Photovoltaic System

The work presented in (Foureaux et al., 2014; Liu et al., 2016) have considered the use of SST in solar system. In such systems, the use of SST provides some advantages such as compactness and cable solution, power quality enhancement, ease of maintenance and fault ride through capability.

Wind Energy Conversion System

From the work reported in (Kadandani, Dahidah, & Ethni, 2021a; Gao et al., 2015), SST has been considered as a substitute for the conventional LFT, STATCOM and other reactive power support circuitries in wind energy conversion system.

Subsea Application

As an emerging technology, the SST is being foreseeing as a possibe option in subsea application especially in oil and gas sectors. Thus, the small footprint nature of SST makes it suitable in such applications as volume and weight are critical.

Aircraft System

Similar to subsea applications, the aircraft system also has some constrains interms of space and volume. As such, the SST would be a preferred choice against the conventional LFT.

CONCLUSION

The SST has been considered as promising alternative to conventional LFT in voltage transformation with additional ancillary functionalities in electrical power systems based applications. This paper has investigated the much anticipated functionalities of SST required to support electrical grid in tackling the challenges of large proliferation of renewable energy sources, adoption of electric vehicle charging system, connection of non-linear loads among others that forces the grid to deal with transients. The paper has also explored other critical areas that requires the unique features of SST such as compactness/reduced footprint, space and size limitation, cable solution, environmental friendliness and intelligence all of which are not offered by the conventional LFT.

REFERENCES

Das, D., & Kumar, C. (2017). Operation and Control of Smart Transformer Based Distribution Grid in a Microgrid System. *Proceedings of the 2017 National Power Electronics Conference (NPEC), Pune*, 135-140.

Dong, D., Agamy, M., Bebic, J. Z., Chen, Q., & Mandrusiak, G. (2019). A Modular SiC High-Frequency Solid-State Transformer for Medium-Voltage Applications: Design, Implementation, and Testing. *in IEEE Journal of Emerging and Selected Topics in Power Electronics, 7, No. 2*, 768-778. doi:10.1109/JESTPE.2019.2896046

Dujic, D., Zhao, C., Mester, A., Steinke, J. K., Weiss, M., Schmid, S. L., Stefanutti, P. (2013). Power Electronic Traction Transformer: Low Voltage Prototype. *IEEE Transactions on Power Electronics, 28*(12), 5522–5534.

Eshkevari, A. L., Mosallanejad, A., & Sepasian, M. (2020). In-depth Study of the Application of Solid-State Transformer in Design of High-Power Electric Vehicle Charging Stations. *IET Electrical Systems in Transportation* (10, issue 3), 310-319.

Foureaux, N. C., Adolpho, L., Silva, S. M., Brito, J. A. d. S., & Cardoso Filho, B. d. J. (2014). Application of Solid State Transformers in Utility Scale Solar Power Plants. *Proceedings of the 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC)*, 3695-3700. doi:10.1109/PVSC.2014.6924909

Gao, R., Husain, I., Wang, F., & Huang, A. Q. (2015). Solid-State Transformer Interfaced PMSG Wind Energy Conversion System. *Proceedings of IEEE Applied Power Electronics Conference and Exposition (APEC)*, 1310-1317.

Gao, R., Husain, I., & Huang, A. Q. (2016). An Autonomous Power Management Strategy Based on DC Bus Signalling for Solid-State Transformer Interfaced PMSG Wind Energy Conversion System. *Proceedings of IEEE Applied Power Electronics Conference and Exposition (APEC)*, 3383-3388.

Gao, R., She, X., Husain, I., & Huang, A. Q. (2017). Solid-State-Transformer-Interfaced Permanent Magnet Wind Turbine Distributed Generation System with Power Management Functions. *IEEE Transactions on Industry Applications, 53*(4), 3849-3861.

Hambridge, S., Huang, A.Q., & Yu, R. (2015). Solid State Transformer (SST) as an Energy Router: Economic Dispatch Based Energy Routing Strategy. *Proceedings of IEEE Energy Conversion Congress and Exposition (ECCE)*, 2355-2360.

Hannan, M. A., Ker, P. J., Lipu, M. S. H., Choi, Z. H., AbdRahman, M. S., Muttaqi, K. M., & Blaabjerg, F. (2020). State of the Art of Solid-State Transformers: Advanced Topologies, Implementation Issues, Recent Progress and Improvements. *IEEE Access, 8*, 19113-19132.

Huang, A. Q. (2016). Medium-Voltage Solid-State Transformer: Technology for a Smarter and Resilient Grid. *in IEEE Industrial Electronics Magazine, 10, No. 3,* 29-42. doi:10.1109/MIE.2016.2589061

Huber, J. E., & Kolar, J. W. (2019). Applicability of Solid-State Transformers in Today’s and Future Distribution Grids. *in IEEE Transactions on Smart Grid, 10, No. 1*, 317-326. doi:10.1109/TSG.2017.2738610

Kadandani, N. B., & Abubakar, I. (2023). On Exploring the Power Quality Enhancement Capability and Other Ancillary Functionalities of Solid State Transformer Application in the Distribution System. *Bayero Journal of Engineering and Technology (BJET), 18, No. 2*, 28 – 39.

Kadandani, N. B., Dahidah, M., & Ethni, S. (2021a). An Overview of the Role of Solid State Transformer in Grid Connected Wind Farms. *Proceedings of the 2021 IEEE 12th International Renewable Energy Congress (IREC2021), Hammamet, Tunisia,* 1 - 6. doi:10.1109/IREC52758.2021.9624851

Kadandani, N. B., Dahidah, M., & Ethni, S. (2021b). An Overview of the Role of Solid State Transformer in Smart Grid. *Proceedings of the 2021 IEEE 12th International Renewable Energy Congress (IREC2021), Hammamet, Tunisia*, 1 - 6. doi:10.1109/IREC52758.2021.9624767

Kadandani, N. B., Dahidah, M., Ethni, S., & Yu, J. (2019). Solid State Transformer: An Overview of Circuit Configurations and Applications. *In the Proceedings of the 15th IET International Conference on AC and DC Power Transmission (ACDC 2019), Coventry, UK*, 1-6.

Kadandani, N. B., & Maiwada, Y. A. (2015a). An Overview of FACTS Controllers for Power Quality Improvement. *The International Journal Of Engineering And Science (IJES), 4*(9), 9-17.

Kadandani, N. B., & Maiwada, Y. A. (2015b). Simulation of a Static Synchronous Compensator (STATCOM) for Voltage Profile Improvement. *IISTE Innovative System Design and Engineering, 6, No 7*, 1-8. Retrieved from http://www.iiste.org/Journals/index.php/ISDE/article/view/23922/24493

Lai, J.S., Mansoor, A.M.A., and Goodman F. (2005). Multilevel Intelligent Universal Transformer for Medium Voltage Application. *Proceedings of IEEE Industrial Appliances Conference*, 1893–1899.

Liu, B., Zha, Y., Zhang, T., & Chen, S. (2016). Solid State Transformer Application to Grid Connected Photovoltaic Inverters. *Proceedings of the 2016 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE)*, 248-251. doi:10.1109/ICSGCE.2016.7876063

Londero, R. P., Mello, A. P. C. d., & Silva, G. S. (2019). Comparison Between Conventional and Solid State Transformers in Smart Distribution Grids. *Proceedings of the 2019 IEEE PES Innovative Smart Grid Technologies Conference - Latin America (ISGT Latin America)*, 1 - 6. doi:10.1109/ISGT-LA.2019.8895327

McMurray, W. (1971). The Thyristor Electronic Transformer: A Power Converter Using a High-Frequency Link. *IEEE Trans. Ind. Gen. Appl., IGA-7, no. 4*, 451–457.

Montoya, R. J. G., Mallela, A., & Balda, J. C. (2015). An Evaluation of Selected Solid-State Transformer Topologies for Electric Distribution Systems. *in the Proceedings of the 2015 IEEE Applied Power Electronics Conference and Exposition (APEC),* 1022-1029. doi:10.1109/APEC.2015.7104474

Nair, A. C., & Fernandes, B. G. (2021). Solid-State Transformer Based Fast Charging Station for Various Categories of Electric Vehicles With Batteries of Vastly Different Ratings. *IEEE Transactions on Industrial Electronics, 68, No. 11*, 10400 - 10411.

Pool-Mazun, E. I., Sandoval, J. J., Enjeti, P. N., & Pitel, I. J. (2020). An Integrated Solid-State Transformer With High-Frequency Isolation for EV Fast-Charging Applications. *IEEE Journal of Emerging and Selected Topics in Power Electronics, 1, No. 1*, 46 - 56.

Qu, Z., Yao, Y., Wang, Y., Zhang, C., Chong, Z., & Abu-Siada, A. (2019). A Novel Unbalance Compensation Method for Distribution Solid-State Transformer Based on Reduced

Order Generalized Integrator. *IEEE Access, 7*, 108593–108603.

Rehman, A., & Ashraf, M. (2019). Design and Analysis of PWM Inverter for 100 KVA Solid State Transformer in a Distribution System. *IEEE Access, 7*, 140152–140168.

Ronanki, D., & Williamson, S. S. (2018). Topological Overview on Solid-state Transformer Traction Technology in High-speed Trains. *2018 IEEE Transportation Electrification Conference and Exposition (ITEC)*, 32-37. doi:10.1109/ITEC.2018.8450135

She, X., & Huang, A. (2013). Solid State Transformer in the Future Smart Electrical System. *in the Proceedings of the 2013 IEEE Power & Energy Society General Meeting*, 1-5. doi:10.1109/PESMG.2013.6672768

She, X., Huang, A. Q., & Burgos, R. (2013). Review of Solid-State Transformer Technologies and their Application in Power Distribution Systems. *IEEE Journal of Emerging and Selected Topics in Power Electronics, 1, No. 3*, 186-198.

She, X., Wang, F., Burgos, R., & Huang, A. Q. (2012). Solid State Transformer Interfaced Wind Energy System with Integrated Active Power Transfer, Reactive Power Compensation and Voltage Conversion Functions. *Proceedings of IEEE Energy Conversion Congress and Exposition (ECCE)*, 3140-3147.

She, X., Yu, X., Wang, F., & Huang, A. Q. (2014). Design and Demonstration of a 3.6-kV–120-V/10-kVA Solid-State Transformer for Smart Grid Application. *in IEEE Transactions on Power Electronics, 29, no. 8*, 3982-3996. doi:10.1109/TPEL.2013.2293471

Steiner, M., & Reinold, H. (2007). Medium frequency topology in railway applications. *12th Eur. Power Electron. Appl. Conf. (EPE), Aalborg, Denmark*, 1-10.

Sun, Q., Li, Y., Ma, D., Zhang, Y., & Qin, D. (2022). Model Predictive Direct Power Control of Three-Port Solid-State Transformer for Hybrid AC/DC Zonal Microgrid Applications. *EEE Transactions on Power Delivery, 7, no. 1*, 528-538. doi:10.1109/TPWRD.2021.3064418

Tahir, Y., Khan, I., Rahman, S., Nadem, M. F., Iqbal, A., Xu, Y., & Rafi, M. (2021). A State-of-the-Art Review on Topologies and Control Techniques of Solid-State Transformers for Electric Vehicle Extreme Fast Charging. *IET Power Electronics*, 1-17. doi: 10.1049/pel2.12141

Wang, J., Huang, A. Q., Sung, W., Liu, Y., & Baliga, B. J. (2009). Smart Grid Technologies. *IEEE Industial Electronics Magazine, 3, No. 2*, 16–23.

Wang, L., Zhang, D., Wang, Y., Wu, B., & Athab, H. S. (2016). Power and Voltage Balance Control of a Novel Three-Phase Solid State Transformer Using Multilevel Cascaded H-Bridge Inverters for Microgrid Applications. *IEEE Transaction on Power Electronics, 31*(4), 3289-3301.

Zhao, C. et al, (2014). Power Electronic Traction Transformer—Medium Voltage Prototype. *IEEE Transactions on Industrial Electronics, 61, No. 7*, 3257–3268.

Zheng, L. et al. (2021). SiC-Based 5-kV Universal Modular Soft-Switching Solid-State Transformer (M-S4T) for Medium-Voltage DC Microgrids and Distribution Grids. *in IEEE Transactions on Power Electronics, 36, No. 10*, 1326-11343. doi: 10.1109/TPEL.2021.3066908