Vol. 05, No. 2 (2023) 325-332, doi: 10.24874/PES05.02.015

Proceedings on Engineering Sciences

www.pesjournal.net

HARMONICS MITIGATION USING DQ TRANSFORM BASED SOLID STATE TRANSFORMER (SST) FOR IT AND CORPORATE BUILDINGS

Jyoti Mohan Kharade [1]
P. M. Joshi

Received 22.12.2022.
Accepted 31.03.2023.
UDC – 621.3.018.3

Keywords:

Solid State Transformer (SST), dq-Transform, Power Quality, Dual Active Bridge Converter (DAB), Harmonic mitigation

A B S T R A C T

The Solid State Transformer (SST) is an advanced power electronics-based key component of the distribution system (SST). This paper presents the application of SST to corporate workspaces and IT environments with nonlinear loads to mitigate harmonics. The three stage SST is designed with rectifier, dual active bridge converter and inverter with suitable converter topologies. The system is controlled with dq-transform based Clarke and inverse Clarke transformation system. The proposed system is designed to eliminate source side current harmonics content by injecting compensating current through inverter. The proposed system is implemented and analyzed for non linear load using MATLAB/ Simulink. The power quality is achieved in terms of improved power factor and decreased % THD to permissible limit.

1. INTRODUCTION

In previous years the majority of heavy industrial fields were only found with non-linear loads, industries such as huge Variable Speed Drives (VSDs), heavy rectifiers, arc furnaces, etc. and it was quite difficult and auditable. In the most recent years, nonlinear loads have been increased rapidly in various commercial, IT, and corporate buildings due to the use of PC gadgets, printers, photocopiers, fax machines, electronic lighting ballasts, fluorescent lighting, fans furthermore, Air-Conditioning and Refrigeration (HVAC) systems, Uninterrupted Power Supply (UPS), etc. Personal desktop computers are generally associated with switched mode power supply since they generally inject harmonics in the current. Such current is mostly conquered by third, fifth, and seventh harmonics (Mahmoud & Shultz, 1982). The interaction of such harmonics current can lead to deterioration of the load power factor of the distribution system (Dolara & Leva, 2012). These are the major influencing sources that can cause the malfunctioning of the current or voltage-sensitive devices. The distortion produced in the current can affect the voltage and produce distortion in the voltage. When currents associated with such harmonics pass through the system it ultimately affects the impedance of the system and creates additional impedance distortion.

An Electrical power system is generally considered to operate with the fundamental frequency. Due to erroneous addition of maximum nonlinear loads increases the

[1] Jyoti Mohan Kharade
Email: Jyoti.kharade99@gmail.com

harmonics which increases the overall total harmonics as compared to individual system harmonics (De La Rosa, 2006). Such huge interacted harmonics current may badly affect the system equipment such as utility meters which may trace incorrect measurements and protective devices such as fuses and circuit breakers.

There is enormous concern about the conventional distribution transformer which supplies Huge nonlinear loads as it affects by overheating of oil, overheating of insulation and winding, extra eddy current passing through metallic parts and heating effect on it, the higher voltage stress on tapings, and bushings. Commonly, the overheating of wiring is produced due to the skin effect but a major concern is when the heating takes place in the neutral conductor connected in a three-phase Line -Neutral connection. For the protection of such a non-linear loaded transformer, additional over-current protection should be added. The efficiency and working life of various systems like motors badly suffer due to overheating. Most of the data communication and data processing equipment may get failed due to such a large nonlinear loaded system with harmonics (Yong et al., 2010) (Mansoor et al. 1995).

Due to harmonics distorted currents, the additional losses take place in the transformer and are influenced majorly by its design parameters like winding configuration, type of conductor material used, insulation properties geometry, and additional attention required to pay to these parameters when the transformer is loaded with non-linear load (Jabbar et al., 2011). Particularly such transformers must be designed with over dimensions to accommodate the additional losses and overheating of it due to nonlinear loads.

On the other hand, Solid State Transformer provides better features to overcome the limitations of typical distribution transformer. The SST employs two stages, three stages or multistage with different converter topologies and control techniques. The review of SST converter topologies (Rathod, 2014), classification and comparison is studied for selection of suitable topologies of SST for mitigation of nonlinear load harmonics (Kharade & Joshi, 2019).

Hence to eliminate source side harmonics content current, SST is proposed with dq transform based control, which injects inverse compensating harmonics current at source side through inverter. Thus the system is implemented and results are analyzed using MATLAB/ Simulink.

2. LITERATURE SURVEY

The most of the research have been conducted to the study the energy profile of industrial, commercial, institute buildings. It mainly focuses on analysis of power quality issues due to non linear loads and provide the solution to mitigate it. The research have been carried out a case study on THD in office buildings and laboratories where the majority load nature is nonlinear including computers, AC, fluorescent lighting systems, cooling systems, SMPs, TVs, etc. It affects significantly the current THD. (Mohd Radzi et al., 2020). The power quality analysis at the laboratory building is conducted and analyzed various power quality issues and harmonics in current. The effect on power factor has been observed, where the harmonic distortion is observed due to nonlinear load devices connected in the system. (Ismail et al., 2012). The power quality parameters observed and analyzed for industrial consumers using LabView (Nicola, et al., 2016). The case study has been carried out about power quality in well-equipped and modern automation systems consisting of energy-efficient buildings. The widespread use of advanced and modern automation system is the key to obtain and energy-efficient operation in buildings for this the advanced technologies mainly consist of nonlinear power electronics devices which increases transmission losses of energy and generates harmonics and affects power quality (Anna Romanksa Zopala et al., 2019). The system has been proposed for the use of distributed DC microgrids with power electronics in commercial buildings. Interconnected DC bus with solar system and batteries with main AC supply was proposed in the system (Wunder et al., 2015). The detailed estimation of small power equipment's energy use and power demand in office buildings is given. Among minor power equipment in offices, the usage of computers is the most significant source of energy consumption. Traditional benchmark comparison methods have drawbacks owing to fluctuating power usage, which are minimized by the methods devised. The models offered have significantly improved forecasts of energy consumption in office buildings, not only in terms of energy consumption but also in terms of small power equipment thermal comfort (Menezes et al.,2014)

3. PROPOSED SYSTEM

The dq-control is nothing but synchronous reference frame control (Jia, et al., 2018) (Udaya Sri et al., 2016). It converts grid voltage and current into a rotating synchronous frame with the grid voltage vector in order to convert three-phase time-varying signals into DC signals. This transition is typically implemented using a phase-locked loop (PLL), which establishes the phase angle of the grid voltage. PI controllers are widely used in dq-control because they are capable of controlling DC signals without introducing steady-state error. Fig. 1 shows the control layout of dq transform-based SST which includes SST first stage control as PI controller, SST second stage controller as PID, and third stage controller as SVPWM controller. For mitigation of harmonic content from the current the DC voltage control, active power, and reactive power control are employed with Clarke and inverse Clarke transformation.

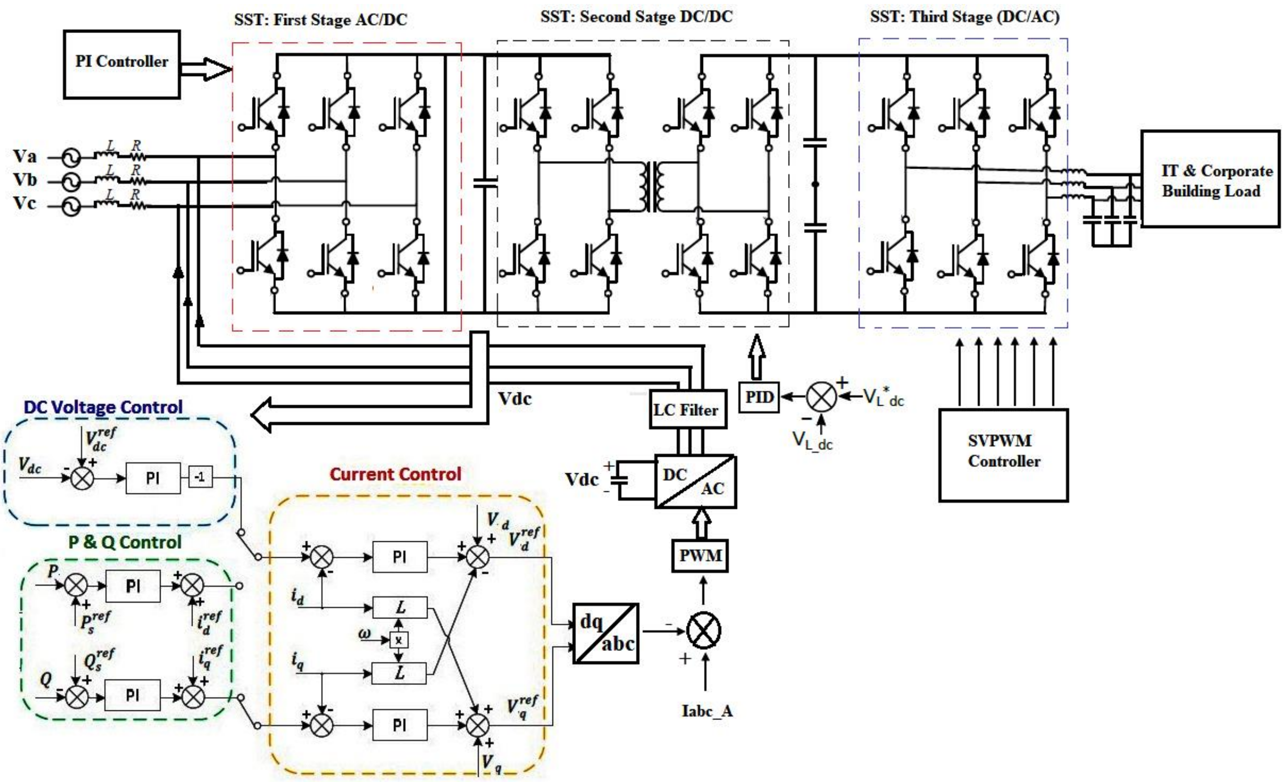

Figure. 1 Control Layout of Dq Transform Based SST

4. SYSTEM DEVELOPMENT

The dq transform-based SST model is designed as shown in fig. 1 and implemented with MATLAB Simulink with the following parameters as shown in Table 1 (Fig.1 & Fig. 2).

Table 1: System parameters for Simulink model of dq-transform based SST

Sr. No	System parameter	Specifications
1	AC Source	V= 11kV f=50 Hz R_S =0.0001 Ohm
2	Load side	R_L= 100 Ohm L_L= 3.3 mH
3	PI Controller	Kp= 0.2 Ki= 25
4	DC Capacitor Voltage	V= 25 kV
5	DC side Capacitor	C= 4.7 μF
6	Rectifier	L= 330mH C= 47 μF
7	SST Transformer	V1=11kV, V2=600V, P(VA)= 10kVA

H. Akaqi first presented the P-Q theory in 1983 (Akagi, et al., 1984). The reactive power and harmonic components are produced using the converter's high-speed response to reduce reactive power and harmonics. The conventional methods of power analysis are insufficient when considering RMS or the average value of variables. A novel method of analyzing and realizing the energy flow in nonlinear circuits has emerged through the use of time domain analysis. The base of the p-q theory is the instantaneous power that is specified in the time domain. The voltage or current waveform can be utilized on a three-phase system with or without a neutral because it is not constrained. Using Clarks' transformation (Singh, et al., 1998), the p-q theory transforms a-b-c coordinates for three-phase currents and voltages to **α**-**β**-0 coordinates and then calculates instantaneous powers on these coordinates (Fig. 2). The Clarke transformation, also known as the **α**-**β**-0 transformation, is used by the p-q theory to convert three-phase components into stationary reference frames using the **α**-**β**-0 transformation. With this technique, the reference current is produced using the non-linear load's instantaneous active and reactive power.

The a-b-c coordinate system's three-phase current or voltage waveforms are transformed into **α**-**β**-0 coordinates. It relates to the Clarke transformation in algebra, where the coordinates - are orthogonal to one another and the coordinate relates to the zero-sequence component.

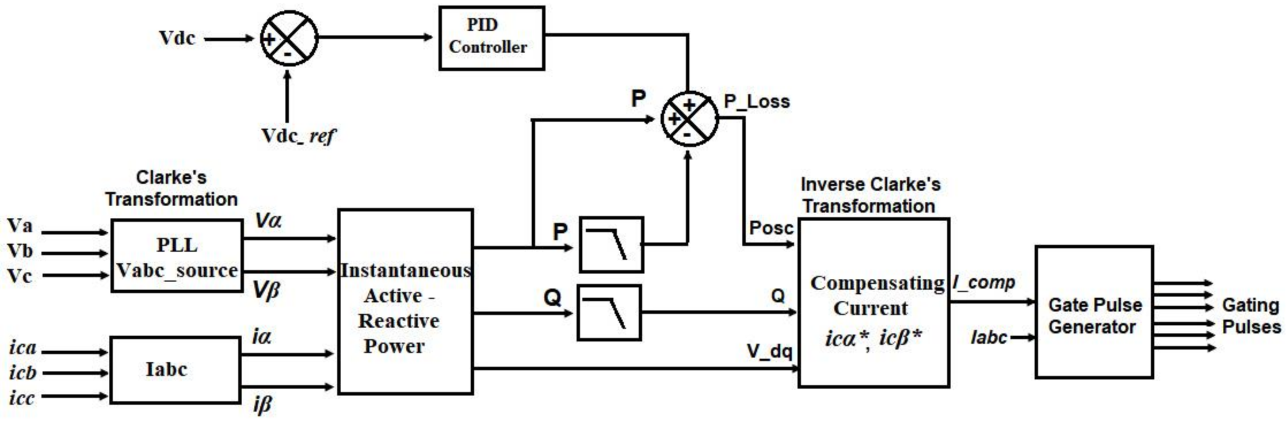

Figure. 2 Inverse harmonic compensating current injection

$$\begin{bmatrix} V\alpha \\ V\beta \\ V0 \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} Vca \\ Vcb \\ Vcc \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} I\alpha \\ I\beta \\ I0 \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} Ica \\ Icb \\ Icc \end{bmatrix} \quad (2)$$

The three-phase **α-β**-0 coordinate system is again applied to the a-b-c coordinate system. An algebraic transformation known as the Inverse Clarke transformation corresponds to this.

$$\begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \\ i0 \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} va \\ vb \\ vc \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v\alpha \\ v\beta \\ v0 \end{bmatrix} \quad (4)$$

As we may define the conventional instantaneous active and reactive power on the three phase circuit are given as,

$$p = v_\alpha i_\alpha + v_\beta i_\beta \quad (5)$$

$$q = v_\alpha i_\beta - v_\beta i_\alpha \quad (6)$$

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v\alpha & v\beta \\ -v\beta & v\alpha \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \quad (7)$$

An alternating value and a mean value can be resolved by P and q. P and Q are generated by the load current's harmonic components, whereas p and q are generated by the load current's positive sequence components.

The active power filter should supply all of the oscillating parts of p and q. Consequently, the necessary compensatory currents can be determined as,

$$p = \bar{p} + \tilde{p} \quad (8)$$

$$q = \bar{q} + \tilde{q} \quad (9)$$

The instantaneous active power p and reactive power q are used to calculate the compensating current ic**α** and ic**β**.

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \begin{bmatrix} v\alpha & v\beta \\ -v\beta & v\alpha \end{bmatrix}^{-1} \begin{bmatrix} \bar{p} \\ q \end{bmatrix}$$

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v\alpha & -v\beta \\ v\beta & v\alpha \end{bmatrix}^{-1} \begin{bmatrix} \bar{p} \\ q \end{bmatrix} \quad (10)$$

Instantaneous active current on the α axis $ic\alpha*$ and Instantaneous reactive current on the β axis $ic\beta*$ is given as

$$ic\alpha* = \frac{V\alpha}{v_\alpha^2 + v_\beta^2} \cdot \bar{p} \frac{V\beta}{v_\alpha^2 + v_\beta^2} \cdot q \quad (11)$$

$$ic\beta* = \frac{V\beta}{v_\alpha^2 + v_\beta^2} \cdot \bar{p} - \frac{V\alpha}{v_\alpha^2 + v_\beta^2} \cdot q \quad (12)$$

$$\begin{bmatrix} ica^* \\ icb^* \\ icc^* \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c\alpha^*} \\ i_{c\beta^*} \end{bmatrix} \quad (13)$$

The three phase reference compensating currents ica*, icb*, and icc* are fed into the hysteresis current controller. Nonlinear loads cause harmonics to be produced and injected into the power system. The hysteresis current controller uses the computed compensating three phase currents from the instantaneous reactive power theory (ica*, icb*, icc*) as reference currents. The controller switches for the hysteresis current will receive pulses produced by the controller. At the end, the controller will produce compensatory currents (ica*, icb*, and icc*) and inject them into the power system.

As a result, the power system's need for reactive power drops. By the way, the system's harmonics are lower due to the decreased need for reactive power. The power factor is enhanced while the THD value is reduced.

5. RESULT DISCUSSION:

The system is analyzed for non linear load conditions. Fig. 3 shows the load side voltage, current profile, which indicates the impact of non linear load with harmonics content. The fig. 4 illustrates the source side voltage, current profile, which clearly indicates the elimination of harmonic content from current waveform with proposed and implemented dq control.

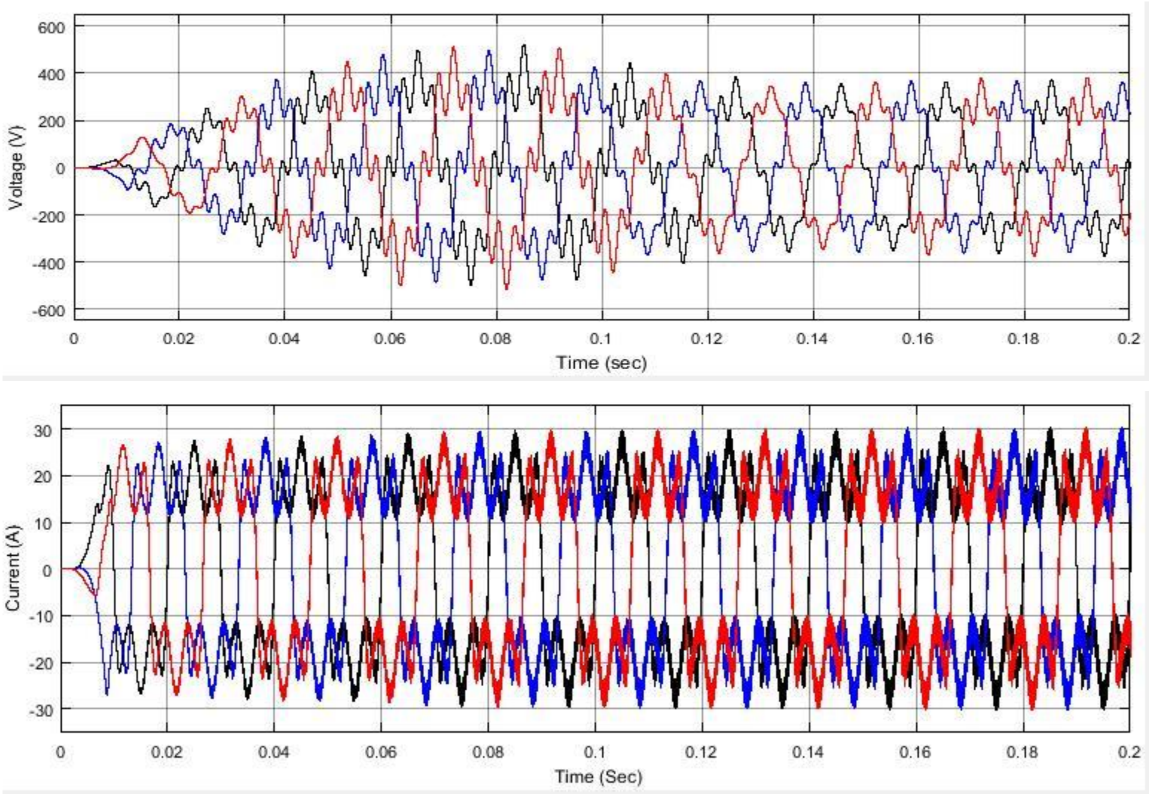

Figure. 3 Load side voltage and current profile with non linear load

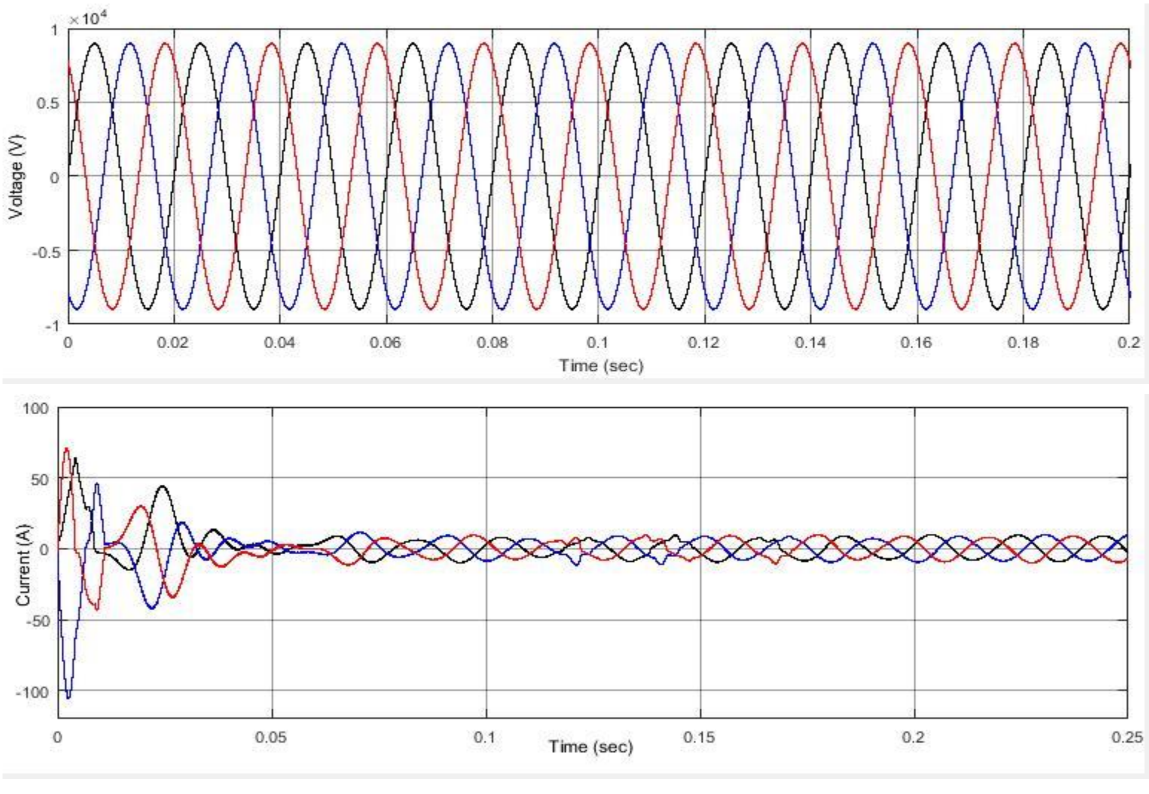

Figure. 4 Source side voltage and current profile for dq transform based SST

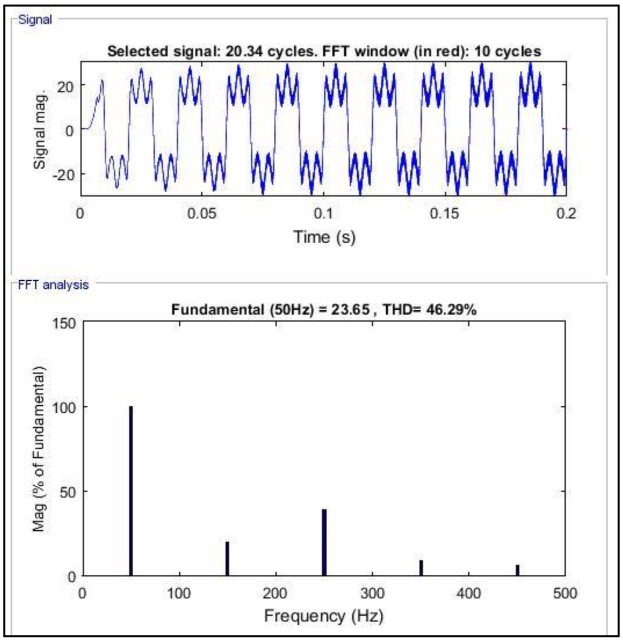

Figure. 5 Load side harmonics frequency spectrum and THD profile for SST with non linear load

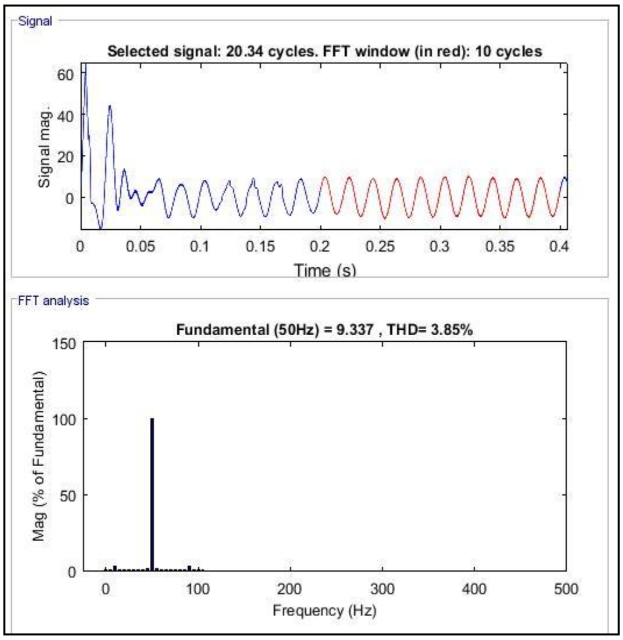

Figure. 6 Source side harmonics frequency spectrum and THD profile for SST with dq transform

The frequency spectrum analysis (FFT) of a non-linear load-connected SST at load side is illustrated in Fig. 5. The odd harmonics content is injected at load side due to non linear loads. It shows the content of 3^{rd}, 5^{th}, 7^{th}, 9^{th} and 11^{th} harmonics in the THD (Total Harmonic Distortion) analysis. After compensation, the source side harmonic current content get mitigated and approximately pure fundamental waveform is maintained at source side as illustrated in fig. 6. The % THD is decreased from 46.29 % to 3.85 % except for power loss caused by switching components. This suggests that dq-transform-based SST control can more effectively reduce harmonic content in the system and this control can reduce the reactive current in the system more effectively.

The source current THD is now lower than the permissible limit of 5% given by the IEEE 519-2014 standard. The system in which the source current's significant improvement in terms of total harmonic distortion (THD) of source current standards can be seen. Moreover, we can also get better power factor's correction (PF) due to employment of Vienna rectifier.

6. CONCLUSION:

Thus the new advanced power electronics based Solid State Transformer (SST) is employed to provide power quality improvement features. The harmonics generated due to non linear load in IT and corporate building injects odd harmonics at source side current. To avoid power quality issues and unbalancing of the grid or source side, the SST can be used with effective dq transform based control. The three stage SST is implemented and analyzed the impact of non linear load at source side. This proposed method provides the solution to inject exact inverse compensating current to mitigate harmonics at source side. The implemented MATLAB Simulink model of SST based on dq transform shows the source current THD as 3.81% which is lower than 5 %, permissible limit set by IEEE 519-2014 standard. The system shows noticeable improvement in the source current's total harmonic distortion (THD) compared to source current norms. In addition, the Vienna rectifier provides the better power factor (PF) correction. Thus the system can be tested on the basis of different parameters such as %THD, power factor, response time, number of switches needed, switching losses, etc. It is obvious that the SST system based on the dq-transform is efficient to mitigate harmonic current content reflected in source side current from non linear load.

References

Akagi, H., Kanazawa, Y., & Nabae, A. (1984). Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components. *IEEE Transactions on Industry Applications*, *IA–20*(3), 625–630. doi: 10.1109/tia.1984.4504460

De La Rosa, F. C. (2006). Harmonics and Power Systems. *CRC Press*. doi: 10.1201/9781420004519.

Dolara, A., & Leva, S. (2012). Power Quality and Harmonic Analysis of End User Devices. *Energies*, *5*(12), 5453–5466. doi: 10.3390/en5125453

Ismail, B., Arshad, M. H., Thangaprakash, et al. (2012). Power Quality Monitoring and Analysis of a Laboratory Building.*The 2nd International Malaysia-Ireland Joint Symposium on Engineering, Science and Business (IMiEJS2012),* 899-906.

Jabbar, R. A., Junaid, M., Ali Masood, M., & Saeed Akhtar, K. (2009). Impacts of harmonics caused by Personal Computers on distribution transformers. *Third International Conference on Electrical Engineering*. doi: 10.1109/icee.2009.5173191.

Jia, J., Yang, G., Nielsen, A. H., & Rønne-Hansen, P. (2018). Study of control strategies of power electronics during faults in microgrids. *Hybrid-Renewable Energy Systems in Microgrids.* 109–146. doi: 10.1016/B978-0-08-102493-5.00007-8.

Jyoti, M., Kharade, P., & Joshi M. (2019). A Access of SST Converter Topologies: Control & Modulation Techniques. *International Journal of Recent Technology and Engineering, 8.* 873-878. doi: 10.35940/ijrte.B1143.0982S1119.

Mahmoud, A. A., & Shultz, R. D. (1982). A method for analyzing harmonic distribution in AC power systems. *IEEE Transactions on Power Apparatus and Systems, vol. PAS-101, 6, pp. 1815–1824.* doi:10.1109/TPAS.1982.317235.

Mansoor, A., Grady, W., Staats, P., Thallam, R., Doyle, M., & Samotyj, M. (1995). Predicting the net harmonic currents produced by large numbers of distributed single-phase computer loads. *IEEE Transactions on Power Delivery, 10*(4), 2001–2006. doi: 10.1109/61.473351

Menezes, A., Cripps, A., Buswell, R., Wright, J., & Bouchlaghem, D. (2014). Estimating the energy consumption and power demand of small power equipment in office buildings. *Energy and Buildings, 75*, 199–209. doi: 10.1016/j.enbuild.2014.02.011

Mohd Radzi, M. Z., Azizan, M. M., & Ismail, B. (2020). Observatory case study on total harmonic distortion in current at laboratory and office building. *Journal of Physics: Conference Series*, *1432*(1), 012008. doi: 10.1088/1742-6596/1432/1/012008.

Nicola, C. I., Voicu, V., Popescu, S., Niţu, M. C., Iovan, D., Duţă, M., ... & Andreescu, S. (2016). Monitoring and Analysis of the Electrical Parameters for an Industrial Consumer using LabVIEW Environment. *Annals of the University of Craiova, Electrical Engineering series*, (40).

Rathod, D. K (2014). Solid State Transformer (SST): Review of Recent Developments. *Advance in Electronic and Electric Engineering, 4,* 45-50.

Romanska-Zapala, A., Dechnik, M., & Grzywocz, K. (2019). Power Quality in Energy Efficient Buildings – a Case Study. *IOP Conference Series: Materials Science and Engineering*, *603*(5), 052020. doi: 10.1088/1757-899x/603/5/052020

Singh, B., Al-Haddad, K., & Chandra, A. (1998). Harmonic elimination, reactive power compensation and load balancing in three-phase, four-wire electric distribution systems supplying non-linear loads. *Electric Power Systems Research*, *44*(2), 93–100. doi: 10.1016/s0378-7796(97)01187-5

Udaya Sri, B., Rao, P. A. M., Mohanta, D. K., & Varma, M. P. C. (2016). Improvement of power quality using PQ-theory shunt-active power filter. *2016 International Conference on Signal Processing, Communication, Power and Embedded System (SCOPES)*. doi: 10.1109/scopes.2016.7955815

Wunder, B., Kaiser, J., Fersterra, F., Ott, L., Han, Y., & Marz, M. (2015). Energy distribution with DC microgrids in commercial buildings with power electronics. *2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST)*. doi: 10.1109/sedst.2015.7315246

Yong, J., Chen, L., & Chen, S. (2010). Modeling of Home Appliances for Power Distribution System Harmonic Analysis. *IEEE Transactions on Power Delivery*, *25*(4), 3147–3155. doi: 10.1109/tpwrd.2010.2051960

Jyoti Mohan Kharade
Annasaheb Dange College of Engineering and Technology Ashta,
Research Scholar, Shivaji University , Kolhapur
Maharashtra, India
jyoti.kharade99@gmail.com
ORCID 0000-0002-8884-5387

P. M. Joshi
Government College of Engineering, Karad,
Research Guide, Shivaji University , Kolhapur
Maharashtra, India
dr.pmjoshi@gmail.com
ORCID 0000-0002-5784-8200