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# Efficient design of 'High Power and Low Loss DC-DC Converter Using Modified PQ Theory'

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***Abstract***

*The use of LCL DC-DC converters in high efficiency mining applications for Megawatt range power transport has gone up in past years. . These converters comprise LCL tank resonant circuit between two voltage source converters in which the losses are reduced by the use of capacitors. The flows of power between the bridges are also administered for loss reduction. However, the control techniques are more complicated and there are stability issues in real-time implementations. In order to mitigate these issues, this paper proposes a high power and low loss bidirectional LCL converter through assistance of modified pq theory. The study also proposes a constructive control mechanism basing upon the single phase pq theory and Second Order Generalized Integrator (SOGI). Furthermore, Second Order Generalized Integrator (SOGI) are used to generate best orthogonal signals for pq theory. The simulation of proposed efficient LCL converter is developed in MATLAB/SIMULINK environment. The functioning of the LCL converter was analysed under uniform circumstances. The results show that the proposed efficient LCL converter achieved a higher power transfer capability and effectively reduced harmonics. Furthermore, the result was established that the efficiency of the developed control is suitable for mining applications.*

***Keywords****: LCL DC-DC converter, Second Order Generalized Integrator (SOGI), Modified PQ theory, mining applications, active power balance and zero reactive power conditions.*

## 1. Introduction

Electricity is one of the major inventions that have made the lives of human beings easier. Electric current is categorized as Alternating Current (AC) and Direct Current (DC) (Rajkumar, 2009; Abdolkarimzadeh et al., 2017). The AC is used for the domestic purposes while the DC is used for delivery of bulk power used specially for the industrial purpose. DC to DC converter can be defined as an electronic circuit that converts or changes the levels of voltage in direct current (Silva-Ortigoza et al., 2015; Zhang et al., 2015;Tripathi et al., 2015). The range of the power levels vary significantly in various applications. There are low powered batteries in one end of the spectrum while the high voltage power transmission lines are at the other end.. However, the demand for DC power has been increasing with the increase in the number of industries. Lack of stability of the power supply as well as in the DC power system results in frequent power disruptions. This is a major drawback for the industries and hampers the productions. The High Voltage Direct Current (HVDC) power transmission has a significant role to play in connecting separate AC networks (Jahromi et al., 2016). This increase in use in the DC applications has highlighted a few challenges. The major issue arises since the DC systems remain stable till the value it reaches the resonance condition (Jahromi et al., 2017). On reaching the resonance condition the system fails to remain stable.

This stability cannot be achieved using the PQ theory. In order to ensure the mitigation of this issue faced by the DC power system due to the resonance condition, Flexible AC Transmission system (FACTS) is used, with the Unified Power Flow Controller (UPFC). This method ensures the rise in the transmission capacity along with enhancement of the stability of the power system (Shahgholian et al., 2017). In order to prove the stability of the DC power systems Unified Power Quantified Capability (UPQC) is used (Ebadian et al., 2015). This improves the quality of the power and thus the issues of lack of stability during the resonance period could be minimized.



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The requirements of power in various industries and the usage of DC power in the mining industry is also wide (Inamdar et al., 2017). However, with this huge demand of power the quality has deteriorated. The frequent distortion in the sine waves causes harmonics in the current and fluctuations of voltage thus hampering the operation and capability of the electrical equipment. This problem is solved by Unified Power Quality Conditioner (UPQC) (Khorasani et al., 2017). It is important that the increase in the demands for the power needs to be met such that all the industries are able to use it successfully (Bhattacharyya et al., 2014). With this increase restriction on the construction of the new lines as well as the unscheduled power flow creates congestion. The power demand of mining industries are satisfied through the use of series of UPFC and shunt Flexible AC transmission System controllers (Kano et al., 2016).

The above-mentioned section highlights the issues pertaining to the DC-DC converters that are used in the mining industry. In this paper, an efficient high power low loss DC-DC converter is proposed that is developed with the help of modified PQ theory. This research article is organized in the following manner. The second section contains the past works related to the present study. Proposed methodology is discussed in section 3 of this paper. Section 4, contains the simulation results, its discussion and comparison with the other existing techniques. The research paper is concluded in section 5.

## 2. Related Works

Jahromi et al., (2016) suggested DC-based power systems which are used for the mining industries that require a huge amount of power. Along with a huge demand the stability in the power supply is also required. However, the lack of stability in the system during the period of resonance makes it unreliable. The challenges that are faced by this kind of a system includes fault diagnostics and DC protection. The Dual Active Bridge (DAB) is one of the most suitable topologies for the mining technology (Jimichi et al., 2017). However, using this technology the issue of instability during the period of resonance is not completely mitigated. Ebadian et al., (2015) solved the power quality problems of the three-phase four-wire system has excessive null current, voltage sags and voltage swells. Low power and overheating of the transformers are also the results of instability in the current . One of the best solutions that is used is done using UPQC. This assists in solving both the issues. The structure of the UPQC is similar to that of UPFC and ensures the mitigation of the issues of instability in the DC power supply. The major goal of this is to ensure the control of the power flow and ensure stability in the power supply. In the distributed network, the DC components and the harmonics are well balanced.

Bhattacharyya et al., (2014) proposed FACTS controllers namely the Thyristor Controlled Series Compensators (TCSC), the SVC and the UPFC can be successfully used for reduction of the instability of the DC power supply units. The SVC is a shunt connected device which regulates the transmission voltage. The reactive power of the flow control is directly impacted by the use of the static synchronous compensators. Since the main objective of the author is to ensure the minimization of the loss of power and lack of instability of the DC power hence the optimal placement of the FACTS devices is also essential. Zhao et al., (2014) presented High-frequency- link (HFL) to overcome the issue of instability and to ensure suffice of power supply for the industrial use. The Power Conversion Systems (PCSs) has become popular in order to ensure the meeting of the rise in the demand of the electrical power for the industrial use. However, though this method is effective yet the bulky and noisy Line-Frequency (L-F) transformers might hinder the efficiency as well as the power density of the PCS. Park et al., (2014) proposed a model of bidirectional DC to DC converter which is predominantly used in case of automotive hybrid power generators. The fixed-frequency resonant converters which are developed to operate under zero-current switching are used for these bi-directional converters. Using the bi-directional voltage control method two of the processes are combined namely the low voltage side control method and the high voltage side control method.



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Li et al., (2018) proposed a modular isolated soft-switching of the DC to DC converter can be offered that has two-levels of fault tolerance. In each module of the converter, a zero-current switching (ZCS) is used with secondary phase shifted modulations. The normal as well as the faulty operations are simulated as well as verified by the scaled-down prototype experiment. Far et al., (2016) postulated that the high-power DC to DC converters are essential components of the DC grids. This is used to connect to various voltage levels as well as administer the flow of the DC powers through the connected cables. The multiple protection zones can be to achieved with a large meshed DC grid if fault tolerant DC toDC converters are used in the design. Cheng et al., (2017) presented the multistage direct model predictive control is used for DC-DC boost. Based on this predictive controller induction current the output voltage could be achieved without the requirements of additional control loops. Devassy et al., (2017) proposed a modified p-q theory for the integrated unified quality conditioners. Using this system, the quality of the power improvement is done effectively.

## 3. Research methodology

The major concepts of the present proposed techniques are to attain the aspired step ratio, to regulate the capacitor voltage, and to obtain secured and sturdy stable and robust converter process. A supplementary requirement is minimization of the DC faults inside the converter. Fig.1 shows the fundamental LCL topology that comprises of one LCL resonant tank and two converters. This losses in current are minimised through the use of one capacitance in place of high frequency transformers. The flow of power or current is also regulated between the two bridges. Also, few assumptions are considered to employ the steady-state analysis method and minimize the overall complexity of estimations. The DC voltages are taken as constant over a converter modulation period. At the starting phase, all switches, LCL components and diodes are taken to be in lossless and ideal condition.

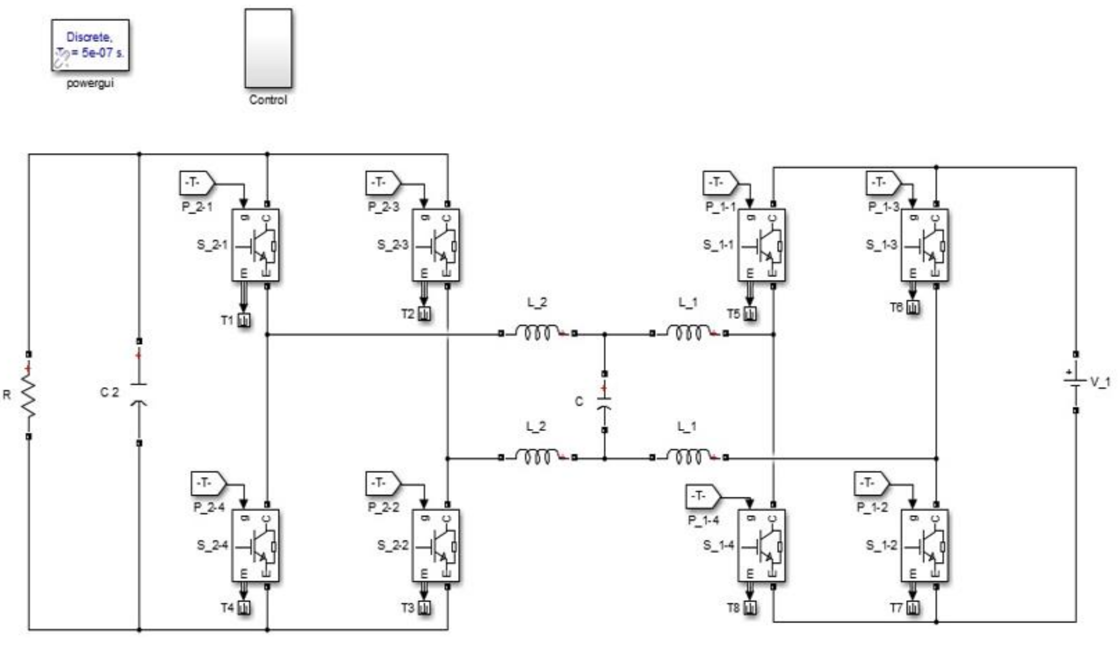


**Fig.1 Fundamental Bidirectional DC/DC converter**

Representative circuit of LCL converter is demonstrated in Fig.2. In this, the two voltage source converters are denoted by pulse voltage sources linked through an LCL resonant tank. Terminal-1 is presumed to be at the source side and terminal-2 is considered as the load side.



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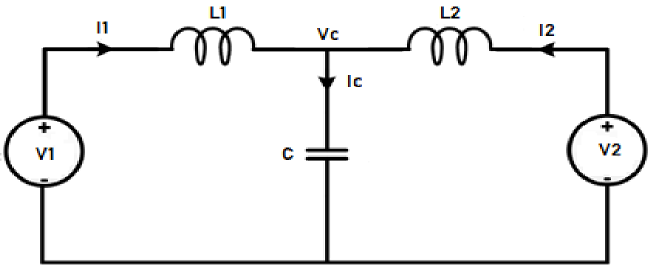


**Fig.2 LCL converter equivalent circuit**

In the proposed LCL converter design, various input parameters are considered such :P is the maximum power (P) transferred to the load, and V1 and V2 are DC voltages of the converter at both sides . Initially, estimate the load side AC voltage ($V_1'$) which is expressed as,

$$V_1' = \frac{4}{\pi} V_1 \quad (1)$$

Then, estimate the load side resistance ($R_1$) using active power balance condition which is given as,

$$P_1 = V_1 . I_1 = \frac{1}{2} \frac{V_1^2}{R_1} \quad (2)$$

Through the application of zero reactive power condition to both sides of the LCL converter circuit. Circuit operates with minimum current magnitudes and hence the switching losses are minimized (Jovcic& Zhang, 2013). Zero reactive power at terminal 1obtains in zero q-element for its current. Hence, the terminal 1 side performs as a resistive load with effective resistance R1.

$$R_1 = -\frac{V_1}{I_1} \quad (3)$$

Then, the proportionality constant K1 and K2 are estimated using design parameter ($\gamma$) value and the mathematical expressions are given below,

$$K_1 = -\frac{V_1}{V_2}\sqrt{1-\gamma^2} \quad (4)$$

$$K_2 = -\frac{V_2}{V_1}\sqrt{1-\gamma^2} \quad (5)$$

Where, $\gamma = \omega C R_1 \frac{V_2}{V_1} < 1.$ If $\gamma$ is equal to 1, the capacitor obtained maximum capacity. The capacitor C in the LCL equivalent circuit is one of the essential components of the converter. Thus, the maximum capacitor limit ($C_{max}$) is expressed as,

$$C_{max} = \frac{V_1}{V_2} . \frac{1}{\omega R_1} \quad (6)$$

Where, $\omega$ is the switching frequency.

Finally, the elements of capacitance C and both side inductance L1 and L2 are estimated by using following equations,

$$C = \gamma . C_{max} \quad (7)$$

$$L_1 = \frac{1-K_1}{\omega^2 C} \quad (8)$$

$$L_2 = \frac{1-K_2}{\omega^2 C} \quad (9)$$

For the authorisation of proposed bidirectional LCL DC-DC converter design, a suitable control technique is required. The proposed control technique is based upon the ideas of functions of converter. It is appropriate to directly work with controlled quantities like active and reactive powers for stimulating the balanced active power condition and zero active reactive power. This is simple process when the control technique depends on the present



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active and reactive power, and pq theory (Akagi et al.).Haque(2002)has explained the modification of three-phase pq theory to a single-phase model. In this model, the primary obstacle is the shifting of single-phase voltages and currents by 90o for attaining orthogonal pseudo signals. Second Order Generalized Integrator (SOGI) technique is one of the best orthogonal signal generation techniques. Fig.3 illustrates the Second Order Generalized Integrator (SOGI).

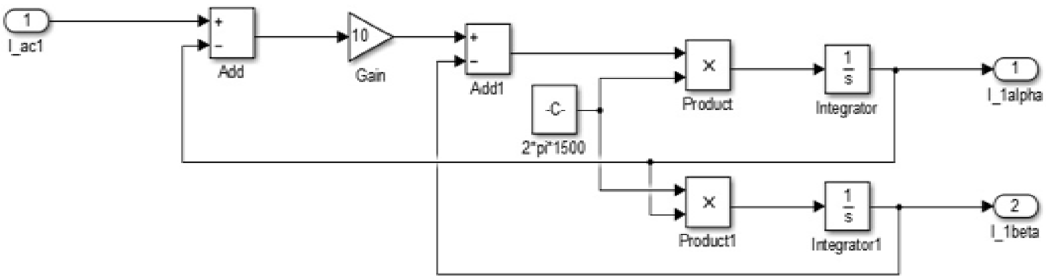


**Fig.3Second Order Generalized Integrator (SOGI)**

Based on these techniques, it can be inferred that the suggested control technique for LCL converter needs the instantaneous measurement of active and reactive powers. In this,Pl and Ql are the desired active and reactive powers of one side of the LCL converter. At that time, the orthogonal components such as ia and ib are the AC current at same side of the LCL converter which are generated by SOGI. Then, the voltage required to generate these Pl and Ql can be estimated based on modified pq theory which is expressed as,

$$\begin{bmatrix} v_a^* \\ v_b^* \end{bmatrix} = \frac{1}{i_a^2+i_b^2}\begin{bmatrix} i_a & -i_b \\ i_b & i_a \end{bmatrix}\begin{bmatrix} P_l \\ Q_l \end{bmatrix} \qquad (10)$$

Where, $v_a^*$ and $v_b^*$ are the components of reference voltages .These components are used to measure the magnitude of reference voltage .The phase shift is dependent on the reference obtained from SOGI. These determined values are used to develop the modulation scheme of the converter. The magnitude reference voltage and phase shifts are expressed as,

$$v_m^* = \sqrt{v_a^{*2} + v_b^{*2}} \quad (11)$$

$$b^* = \text{atan}\,(v_b^*/v_a^*) (12)$$

Using magnitude reference voltage ($v_m^*$), the magnitude index is expressed as follows,

$$M^* = \frac{\sqrt{2\pi}}{4V_{dc}}.v_m^* \qquad (13)$$

Fig.4shows that the one control block using modified pq theory, that is employed to a bridge at one side of the LCL converter. Similarly, the control block is employed to the other bridge at another side of the LCL converter.

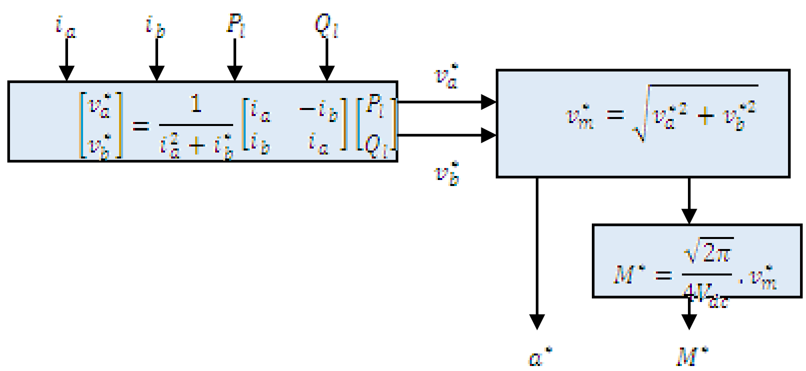


**Fig.4Control block using PQ theory.**


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Then, the full control architecture is achieved by employing zero reactive power on each sides of the LCL converter and through power balance between the two bridges. Fig.5 shows that the proposed control technique for LCL converter using SOGI and pq theory. The diagram shows the single use of PIcontroller in the whole control system, which leads to a balanced system. It also implies easy tuning of control and efficient implementation of the hardware.

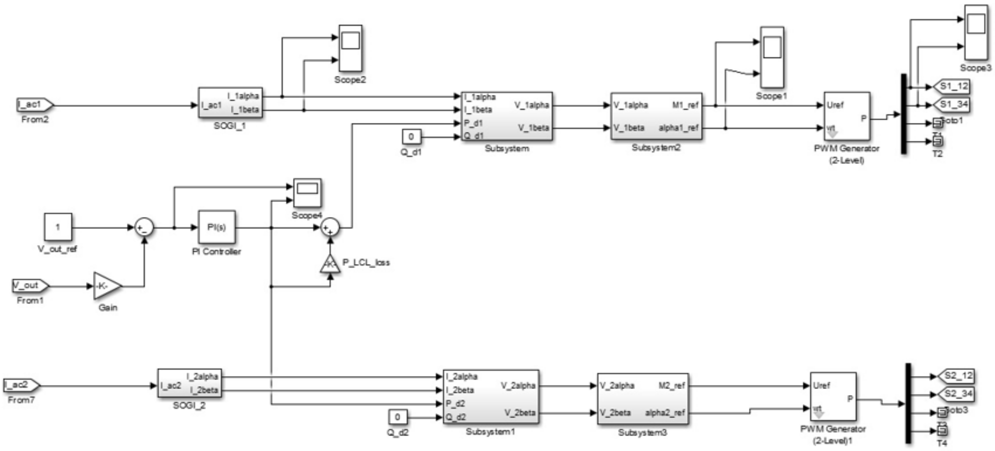


**Fig.5 Proposed control technique for the LCL converter using SOGI and pq theory**.

The suggested LCL converter design is meant to achieve the aspired performance by limiting the voltage in capacitor, and to attain secured and sturdy converter process.

## 4. Results and Discussion

In order to validate the performance of proposed LCL converter design, this paper realized a LCL converter with100MW and 300kV/20 kV in MATLAB/SIMULINK software. Generally, the proposed DC-DC converter design is built using two H-bridges and both the bridges are connected with a filter circuit namely LCL network. The H-bridges are constructed using IGBT switches. This DC-DC converter functioning as the DC transformer to step-up or step down the DC voltage level of the technique with high power capacity of 100MW. The voltage level of the terminal-1 is 300kV and the terminal-2 voltage level is the 20kV. Hence, the converter is used to work as the bidirectional converter. Table I shows that the simulation parameters of the proposed LCL converter. In the proposed LCL converter, second order generalized integrator (SOGI) and PQ-theory are used for the control purpose and to reduce the loss of the converter circuit. The control technique designed to transfer the maximum power that is the real power (P) and other power component as reactive power (Q) is set to zero. Therefore, we need to consider the load connected as resistive load (R2=3.2423 Ohms). Also, using filter capacitance at the load side (C2=100uF) to reduce the ripple factor of load.

**Table I. Simulation parameters**

| Parameters | Values |
|---|---|
| Maximum Power(P) | 100 MW |
| Voltage of terminal 1 ($V_1$) | 300 kV |
| Voltage of terminal 2 ($V_2$) | 20 kV |
| Capacitor (C) | 1.4181 µF |
| Inductor-1 ($L_1$) | 98.4 mH |
| Inductor-2 ($L_2$) | 8.3 mH |
| Switching frequency ($\omega$) | 1500 Hz |
| Design parameter ($\gamma$) | 0.65 |


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The LCL resonant tank circuit operates in a manner similar to that of an AC transformer. Here the capacitor voltage takes sinusoidal waveform. Then, active power flows from terminal 1 to terminal 2.By using equation 3; it can be found out that I1 has an 180ophase shift relative to voltage V1. The AC voltage and current for the bridge 2 are in phase with each other. Similarly, V2 and I1 are in phase with each other. The stress level on the switches are minimised through Zero current switching at both sides of inductance. Fig.6 and Fig.7 shows the output current through inductor L1and inductor L2respectively.

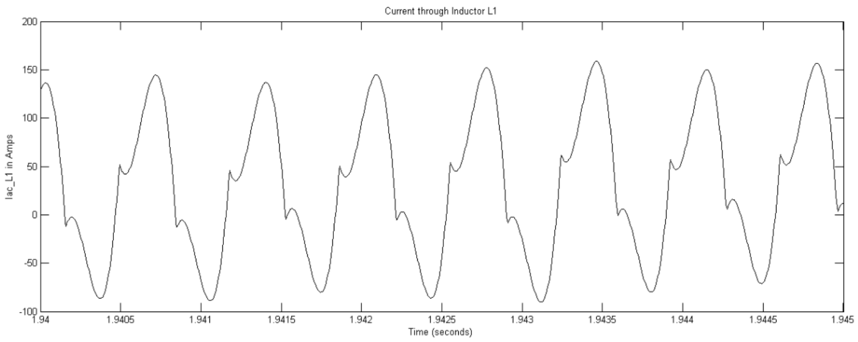


**Fig.6 Output current through inductor L1**

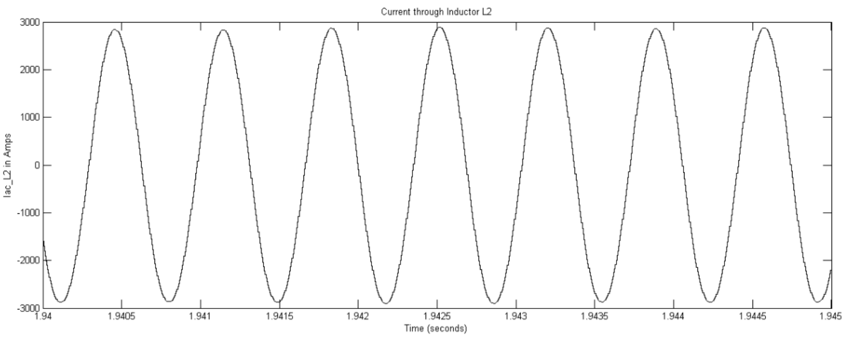


**Fig.7 Output current through inductor L2**

In the proposed LCL converter, the output load power achieved stable power as 100 MW at below 0.2 seconds. Similarly, the output load voltage obtained stable voltage 20 kV at below 0.2 seconds. Fig.8 and Fig.9 shows that the output load power and output load voltage respectively.

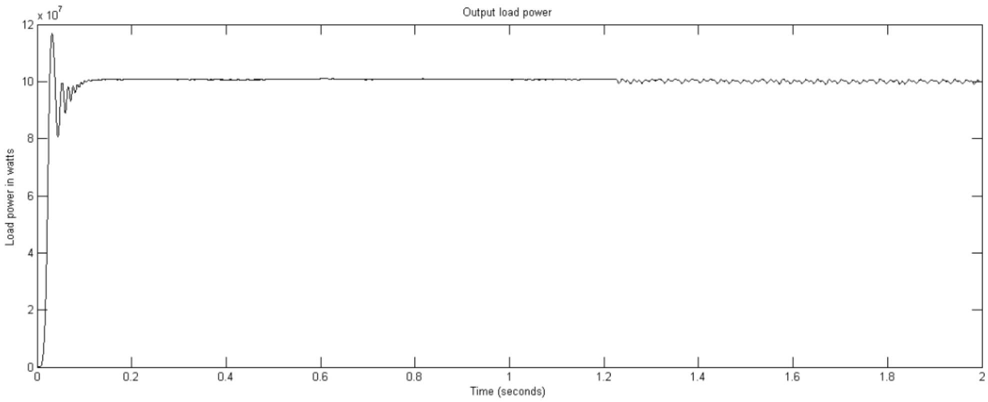


**Fig.8 Result of output load power**



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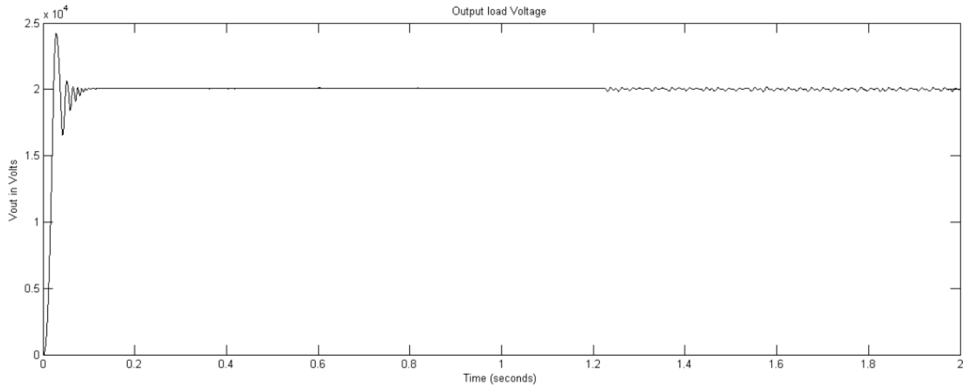


**Fig.9 Result of output load voltage**

The proposed LCL resonant tank circuit produced the pure sinusoidal waveform without harmonics based on proposed control technique using SOGI and modified pq theory. Fig.10 shows that the output voltage across resonant capacitor (Vc).

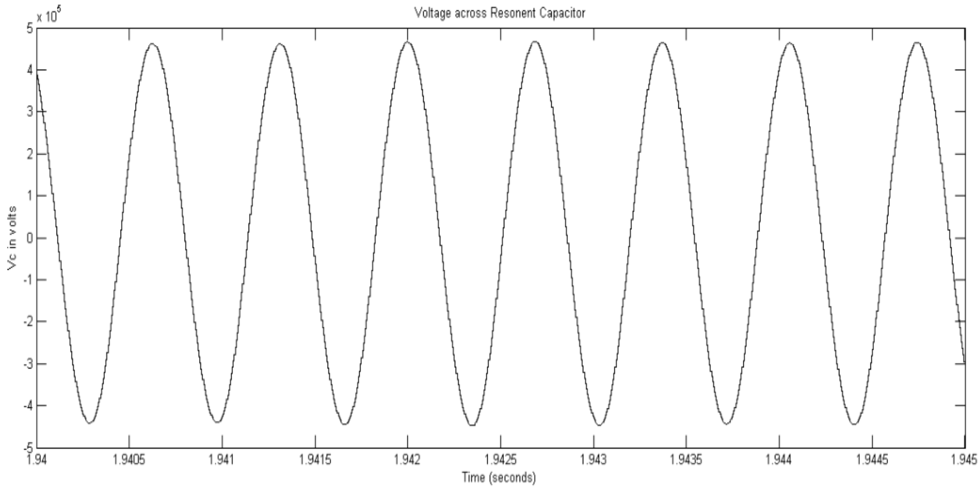


**Fig.10 Result of output voltage across resonant capacitor**

The proposed LCL DC-DC converter achieved a greater stability by setting the design parameter ($\gamma$) value to 0.65. Also, it reduces the losses and stress on switches by setting appropriate $L_2$ value which greatly reduces the harmonics. Therefore, the proposed LCL DC-DC converter achieved a greater power transfer capability using SOGI and modified pq theory in the control strategy.

## 5. Conclusion

In this paper, efficient high power and low loss LCL DC-DC converter using the modified p-q theory is proposed for mining applications. The LCL resonant tank circuit is designed based on introducing active power balance and zero reactive power conditions. In addition, an elementary and constructive control technique is suggested with fundamental principles that is rooted upon single phase p-q theory and Second Order Generalized Integrator (SOGI). The simulation of proposed efficient 100 MW and 300kV/20 kV LCL converter is designed in MATLAB/SIMULINK environment and its functioning has been evaluated under balanced conditions. The simulation results illustrate that the proposed bidirectional LCL DC-DC converter achieved a higher power transfer capability and effectively reduced harmonics. Moreover, it is confirmed that the effectiveness of the proposed control technique.



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**References**

[1] Inamdar, M.J.J. and Desai, M.R.S., 2017. PQ theory based design of Unified Power Quality Conditioner for tranquillization of voltage and current unbalance under Non Linear Load condition.

[2] Rajkumar, N. (2009). Direct current and alternating current systems. Electrical Engineering-Volume I, 108.

[3] Abdolkarimzadeh, M., Nazari-Heris, M., Abapour, M., & Sabahi, M. (2017). A Bridge Type Fault Current Limiter for Energy Management of AC/DC Microgrids. IEEE Transactions on Power Electronics.

[4] Silva-Ortigoza, R., Hernández-Guzmán, V. M., Antonio-Cruz, M., & Munoz-Carrillo, D. (2015). DC/DC Buck power converter as a smooth starter for a DC motor based on a hierarchical control. IEEE Transactions on Power Electronics, 30(2), 1076-1084.

[5] Tripathi, A. K., Mainali, K., Patel, D. C., Kadavelugu, A., Hazra, S., Bhattacharya, S., &Hatua, K. (2015). Design considerations of a 15-kV SiC IGBT-based medium-voltage high-frequency isolated DC–DC converter. IEEE Transactions on Industry Applications, 51(4), 3284-3294.

[6] Zhang, C., Wang, J., Li, S., Wu, B., & Qian, C. (2015). Robust control for PWM-based DC–DC buck power converters with uncertainty via sampled-data output feedback. IEEE Transactions on Power Electronics, 30(1), 504-515.

[7] Jahromi, M.G., Mirzaeva, G. and Mitchell, S.D., 2016, October. Design of a high power low losses DC-DC converter for mining applications. In Industry Applications Society Annual Meeting, 2016 IEEE (pp. 1-8). IEEE.

[8] Jahromi, M. G., Mirzaeva, G., & Mitchell, S. D. (2017). Design and Control of a High-Power Low-Loss DC–DC Converter for Mining Applications. IEEE Transactions on Industry Applications, 53(5), 5105-5114.

[9] Shahgholian, G., Mahdavian, M., Janghorbani, M., Eshaghpour, I. and Ganji, E., 2017, June. Analysis and simulation of UPFC in electrical power system for power flow control. In Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2017 14th International Conference on (pp. 62-65). IEEE.

[10] Ebadian, M., Talebi, M. and Ghanizadeh, R., 2015. A new approach based on instantaneous power theory for improving the performance of UPQC under unbalanced and distortional load conditions. AUTOMATIKA: časopiszaautomatiku, mjerenje, elektroniku, računarstvoikomunikacije, 56(2), pp.226-237.

[11] Bhattacharyya, B., Gupta, V.K. and Kumar, S., 2014. UPFC with series and shunt FACTS controllers for the economic operation of a power system. Ain Shams Engineering Journal, 5(3), pp.775-787.

[12] Kano, M., Maekawa, T., Takeshita, T., & Kunii, Y. (2016, November). Comparison of converter arrangement of series and shunt converters in UPFC for distribution system control. In Renewable Energy Research and Applications (ICRERA), 2016 IEEE International Conference on (pp. 431-436). IEEE.



ISSN: 2005-4238 IJAST

[13] Khorasani, P. G., Joorabian, M., &Seifossadat, S. G. (2017). Smart grid realization with introducing unified power quality conditioner integrated with DC microgrid. Electric Power Systems Research, 151, 68-85.

[14] Jimichi, T., Kaymak, M., & De Doncker, R. W. (2017, June). Comparison of single-phase and three-phase dual-active bridge DC-DC converters with various semiconductor devices for offshore wind turbines. In Future Energy Electronics Conference and ECCE Asia (IFEEC 2017-ECCE Asia), 2017 IEEE 3rd International (pp. 591-596). IEEE.

[15] Zhao, B., Song, Q., Liu, W. and Sun, Y., 2014. Overview of dual-active-bridge isolated bidirectional DC–DC converter for high-frequency-link power-conversion system. IEEE Transactions on Power Electronics, 29(8), pp.4091-4106.

[16] Park, J. and Choi, S., 2014. Design and control of a bidirectional resonant dc–dc converter for automotive engine/battery hybrid power generators. IEEE Transactions on Power Electronics, 29(7), pp.3748-3757.

[17] Li, T. and Parsa, L., 2018. Design, Control, and Analysis of a Fault-Tolerant Soft-Switching DC–DC Converter for High-Power High-Voltage Applications. IEEE Transactions on Power Electronics, 33(2), pp.1094-1104.

[18] Far, A.A.J., Hajian, M., Jovcic, D. and Audichya, Y., 2016. High-power modular multilevel converter optimal design for DC/DC converter applications. IET Power Electronics, 9(2), pp.247-255.

[19] Cheng, L., Acuna, P., Aguilera, R.P., Jiang, J., Wei, S., Fletcher, J. and Lu, D.D.C., 2017. Model Predictive Control for DC-DC Boost Converters with Reduced-Prediction Horizon and Constant Switching Frequency. IEEE Transactions on Power Electronics.

[20] Devassy, S. and Singh, B., 2017. Modified pq-Theory-Based Control of Solar-PV-Integrated UPQC-S. IEEE Transactions on Industry Applications, 53(5), pp.5031-5040.

[21] Haque, M. T. (2002). Single-phase PQ theory. In Power Electronics Specialists Conference, 2002. pesc 02. 2002 IEEE 33rd Annual (Vol. 4, pp. 1815-1819). IEEE.

[22] Jovcic, D., & Zhang, L. (2013). LCL dc/dc converter for dc grids. IEEE Transactions on Power Delivery, 28(4), 2071-2079.

[23] Akagi, H., Kanazawa, Y., &Nabae, A. (1984). Instantaneous reactive power compensators comprising switching devices without energy storage components. IEEE Transactions on industry applications, (3), 625-630.



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