Control of Voltage Source Converter (VSC) in Weak Grid Conditions

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By:

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Abstract

Various configurations based on 3-phase voltage source converters (VSC) are used for renewable energy sources like PV and fuel cell systems which inherently provide DC output and require power electronic converters for connecting the power in to the AC grid. In grid connected application, due to disturbances, transients and interruptions, voltage at point of common coupling (PCC), becomes unbalanced and/or fluctuates temporarily. In weak grid, due to large grid impedance, it is more likely to have voltage fluctuations at PCC. VSC used in grid integration, has to work in safe and controlled manner in such conditions. Hence, the control mechanism used for control of VSC in motor drive applications cannot be directly fitted in grid connected VSC application. For VSC to have stable operation in such voltage unbalance and distorted condition, a control mechanism with added functionality is required.

The reliability and stability of VSC is affected by current control strategy as well as the technique used for grid synchronization. Therefore, grid synchronization methods to get stable phase detection of grid voltage and current control mechanism applied to weak grid connected VSC are the main focus of this research work.

Usually, PLL implemented in synchronous reference frame (SRF-PLL) is used for phase detection of positive sequence component of grid voltage. However, in weak grid conditions, due to voltage fluctuation and distortion, the phase detection of SRF-PLL is affected. Also SRF-PLL is not stable to track the phase if grid voltage has harmonic components. In this research use of double synchronous reference frame PLL (DSRF-PLL) with impedance conditioning is proposed. Impedance conditioned DSRF-PLL (ICDSRF-PLL) is able to synchronize the VSC at stronger PCC in weak grid that can give stable enhanced power transfer to grid.

Another important part of VSC operation is current control technique. In presented work a robust predictive current control algorithm is used with ICDSRF-PLL to enhance the stability and power transfer capability of VSC in weak grid. Predictive current control is implemented in ABC reference frame so there is no need to have any parameter transformation in synchronous reference frame which usually the case with PI current control algorithm. In analysis it is found that predictive current control gives fast dynamic response and less current ripple in comparison with PI current control mechanism. Both the concepts presented in this work are verified by MATLAB simulations and hardware using dSPACE.

1. Brief description on the state of the art of the research topic

In last two decades there is a rapid increase in use of distributed power generation through renewable energy sources like solar, wind etc. This enhanced use of distributed power generation necessitates the integration of power converter unit with grid to transfer the electricity through grid. Power electronic interface used for distributed energy sources mainly uses the VSC topology for power electronic converter. [1-3] Two and/or three-level Voltage Source Converter (VSC) topologies has been used for most of the existing grid connected VSC applications like grid integration of renewable energy sources, HVDC transmission, STATCOM etc. This topology can also be implemented by series connection of a large number of semiconductor devices to work in high voltage applications, illustrating that the same topology which is used for low voltage applications can also be used in the high voltage range [4-5].

When VSC is used for grid integration it will be exposed to transients and interruption coming in system and this will create transient unbalanced voltage condition in grid. Especially in weak grid condition where point of common coupling is at far end of distribution system, due to large grid impedance unbalance in voltage becomes more pronounced [6]. For safe operation of VSC during severe voltage unbalanced conditions, it requires control techniques with added functionality which increases the complexity of control system inspired from drive application [7].

Stable and safe Control of VSC mainly affected by grid synchronisation techniques and current control mechanism applied to control system. Therefore intense research efforts applied to development of control system for grid connected VSC in voltage unbalanced conditions. Current controller used for VSC control can be linear or nonlinear in switching [8]. Linear controllers are mainly either PI based or Predictive current regulation based controllers. PI current controller suffers from steady state error while Predictive current Regulation based controller can give precise current tracking with high immunity to load parameter variation [9-10]. A PI Controlled current regulation in stationary reference frame can also give zero steady-state error and good transient performance by transforming the regulator transfer function instead of the ac current error i.e. to transform a desired DC compensation network into an equivalent AC compensation network [11]. Non linear controller requires power devices capable of large switching as well as high rate of rise of voltage capacity. The control algorithm with repetitive control which nullifies the oscillating component of the instantaneous active power at the poles of the converter gives a good performance regarding harmonic distortion factor [12-13]. An improved repetitive control scheme using FIR filter is effective to improve the tracking performance and reduce the harmonic distortion for the grid connected VSI systems [14-15]. Stability of voltage source converter gets compromised when it is connected to non ideal grid [16]. Conventional vector-control strategy applied to voltage-source converters (VSCs) suffer from stability as well as performance problems when it is used to integrate with weak ac grids (i.e. grid with high impedance). Decoupled dq current controller and controller with PLL dynamics can be utilised to overcome the issues of grid connected VSC in weak grid conditions [17-20].

Another important part of control mechanism of grid connected VSC is the grid synchronisation. The main role of the grid synchronization method is to detect the information of grid voltage phase required by the other part of the control system. There is a wide range of methods for grid synchronization has been proposed [21-23]. The most common and widely used grid synchronization technique for VSCs is the SRF-PLL (Synchronous Reference Frame Phase Locked Loop). In ideal condition of grid SRF-PLL is capable of sensing phase and frequency adequately with quite good dynamic response but in non ideal condition i.e. when voltage unbalance occurs or involves harmonic distortion its performance degraded [24-25]. A voltage sensorless approach is developed with virtual flux estimation in [26] but it also suffers from instability in voltage fluctuations and unbalanced voltage condition. For overcoming the problem of unbalanced and distorted voltage in SRF-PLL, double synchronous reference frame PLL (DSRF-PLL) is used and it has given good response in unbalanced voltage condition as well as distorted grid voltage condition. DSRF-PLL when applied in non ideal grid condition its phase detection also gives error in control system of VSC [27-28]. In weak grid condition due to low short circuit ratio (SCR) it imposes the unbalanced and fluctuating voltage condition at PCC. Therefore to get better performance in weak grid condition SRF-PLL with impedance term is presented in [29-30]. This technique works well with unbalanced condition of voltage but not performing adequately in distorted voltage condition which involves harmonics. A control method with feed forward element including PLL dynamics to improve performance of weak grid connected VSC is presented in [31] and PLL with damping factor is presented in [32] to enhance the power transfer limit of VSC in weak grid. However in literature it is not explore to method in which all quality performance can be gained, especially during weak grid conditions. Hence it is required to make further research in this area to achieve a control mechanism involving grid synchronization techniques to give better performance in low SCR PCC of weak grid.

2. Definition of the Problem

Day by day use of grid connected VSC are increasing due to rapid development in the field of distributed energy sources. With this increasing number of grid connected VSC applications, to achieve control of VSC, grid synchronization technique and current control strategy has received significant attention. However, the issues related to control of VSC in unbalanced and distorted voltage condition, especially for weak grid connection of VSC has escaped their attention. The issues for weak grid connected VSC control can be listed as follows:

- Grid synchronization technique should be able to detect phase and frequency of voltage adequately and should not have effect of voltage variation at PCC.
- Current control applied to VSC in coordination with grid synchronization method should be simple in design and less complex to implement.
- Stability of weak grid connected VSC should be increased for enhanced active power transfer to grid.

Hence, the problem can be defined as,

"To develop and implement a grid synchronization technique and a simple yet stable current control mechanism for weak grid connected voltage source converter that enhances the active power transfer to the grid while minimizing the effect of grid impedance."

3. Objective and Scope of work

The operation of the grid connected voltage source converter mainly affected by effectiveness of control strategies and phase detection by the technique used for grid synchronization. Hence reliability and stability of VSC is affected by the stability of control strategies as well as grid synchronization methods. Thus different objectives of proposed research work can be listed out as,

- To design and develop a grid synchronization method which can give precise phase detection of grid voltage at weak PCC of grid in unbalanced and distorted voltage conditions.
- To implement a current control strategy for voltage source converter in ABC reference frame that can achieve stable control of VSC during weak grid conditions.
- To develop a hardware setup to test the combined algorithm of current control and grid synchronization to check the performance of VSC in weak grid connection.

To achieve these objectives, the scope of the work includes following

- Compare the performance of SRF-PLL and DSRF-PLL techniques in weak point of common coupling with voltage fluctuating condition. Also test it for the effect of variation in local load on voltage at PCC. Based on the investigation of issues to arrive at solutions that can overcome it.
- Investigate predictive current control mechanisms that can give stable operation of VSC in non ideal grid condition.
- Implement a combined robust control structure that includes predictive current control and grid synchronization with virtual grid impedance correction.

4. Original contribution by the thesis.

Main contribution of the work presented in this synopsis can summarized as,

1. Comparison of performance of SRF-PLL and DSRF-PLL under fluctuating voltage condition due to weak grid has been carried out to find phase detection issues. This work has shown that DSRF-PLL gives precise phase detection under voltage unbalanced as well as fluctuating conditions while SRF-PLL fails to do so.
2. A corrective action in DSRF-PLL to overcome the problem of weak grid condition namely, a virtual impedance conditioning block to obtain proposed grid synchronization method named ICDSRF-PLL (Impedance conditioned double synchronous reference frame PLL) has been developed in this research work.

   Phase detection by ICDSRF-PLL is evaluated under various conditions like,

- Local load switching at point of common coupling
- Change in active power transfer from VSC to grid.
- Unbalanced voltage condition at PCC.

3. This work has implemented predictive current control in ABC reference frame without use of any parameter for grid connected VSC which makes it simpler and gives faster dynamic response compared to basic PI current controller.
4. Combined control mechanism with ICDSRF-PLL and predictive current control algorithm is developed in MATLAB simulation and tested for various condition of weak grid.

   Moreover, stability of control mechanism is tested for enhanced active power transfer capability by VSC in low SCR (large grid side impedance) point of common coupling of weak grid.
5. Hardware setup for grid connected VSC is developed and results are obtained to validate the proposed combined control mechanism presented in this research work.

6. Methodology of Research, Results / Comparisons

Weak grid connected VSC control is a challenging task as it involves abnormalities like unbalanced voltage and/or fluctuating voltage condition on grid side. For this in the research presented here, issues of VSC weak grid connection is investigated and a grid synchronization technique ICDSRF-PLL is proposed with predictive current controller which not only gives stable operation of VSC during voltage fluctuations but also enhances the active power transfer capability of it in weak grid.

6.1 System Configuration

Fig.1 shows the configuration of system under investigation for proposed work in which the main focus area of the research is highlighted. In system configuration, it can be seen that VSC is connected to grid at PCC through LC filter as well as at PCC local load is also connected to observe effect of load switching on converter operation. Voltage at PCC and converter current is sensed using voltage and current sensor respectively and given to control mechanism. PLL is used to detect grid voltage phase and frequency for synchronizing the VSC at PCC with grid. In control algorithm a linear current controller is used to generate voltage reference for PWM generation block which will generate the required gate signals for power semiconductor switches of 2-level VSC. For this study DC supply of converter is assumed to be constant. As per the focus area, work carried out mainly on two parts, grid synchronization technique and Current controller.

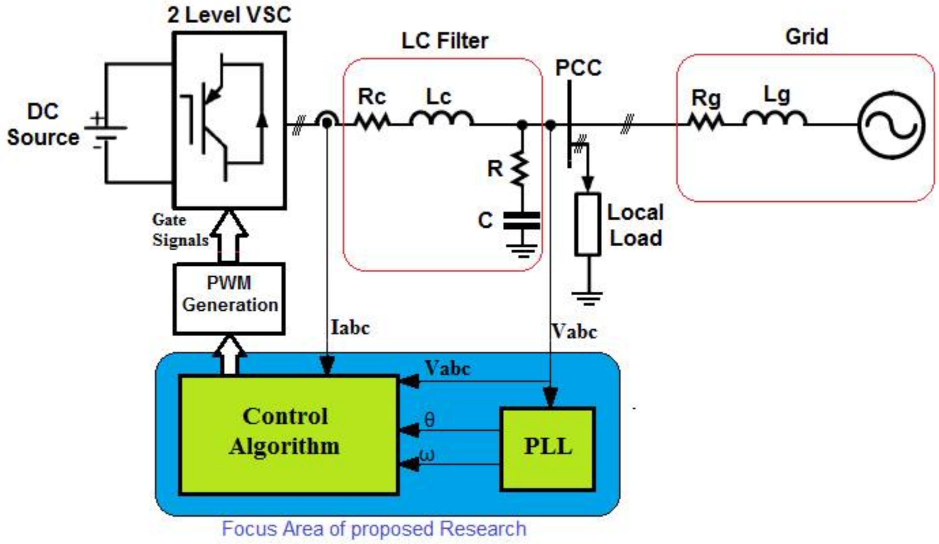


Fig.1 Basic System Configuration

6.1.1 Grid Synchronization

In the applications where there is a requirement of grid integration of power electronic converter, most important is to have information of grid voltage frequency and phase. In SRF-PLL synchronous reference frame voltage is given to PI feedback controller with feed forward component of $\omega = 2\pi f$ (nominal grid frequency) to get synchronization with grid voltage [24]. With proper tuning of PI controller, the grid parameter like voltage frequency and phase angle are detected. However in SRF-PLL only positive sequence component of grid voltage is used to detect the phase and frequency and cross coupling of negative sequence component is not cancelled out, its performance during unbalanced voltage condition gets deteriorated. In grid synchronization with DSRF-PLL, positive and negative sequence component are obtained with double synchronous reference frame rotating opposite to each other [27]. Then cancellation of cross coupling component is achieved using decoupling network as shown in fig.2. The detailed structure of decoupling network positive (+Ve) used in DSRF-PLL is shown in fig.3 and decoupling network negative (-Ve) can be drawn in similar manner.

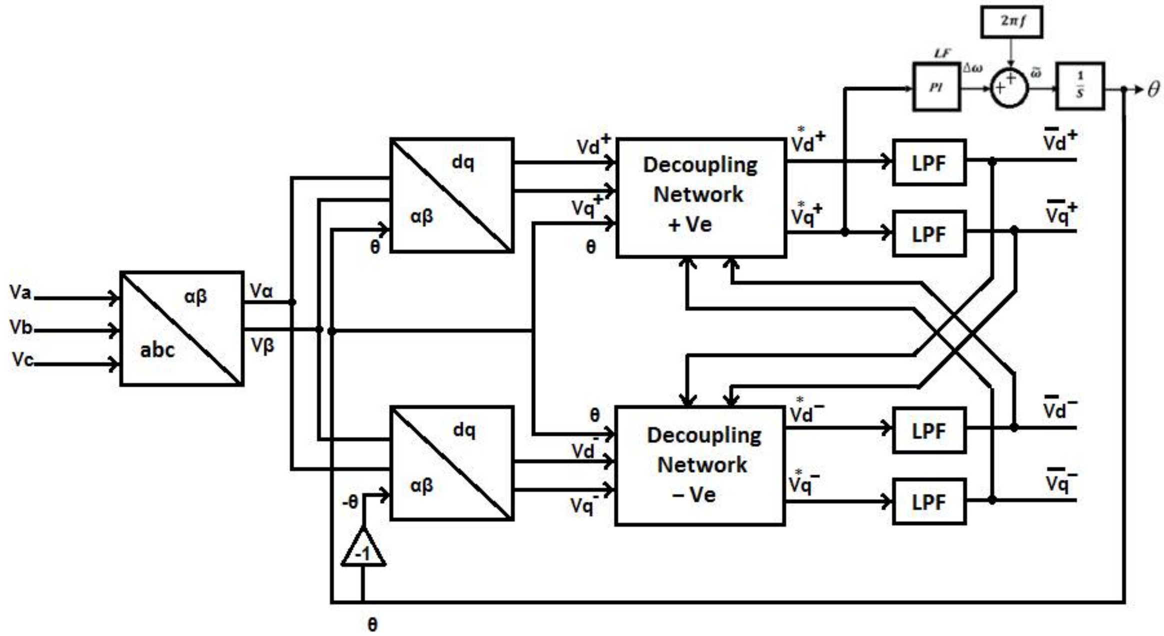


Fig.2 Block diagram of DSRF-PLL

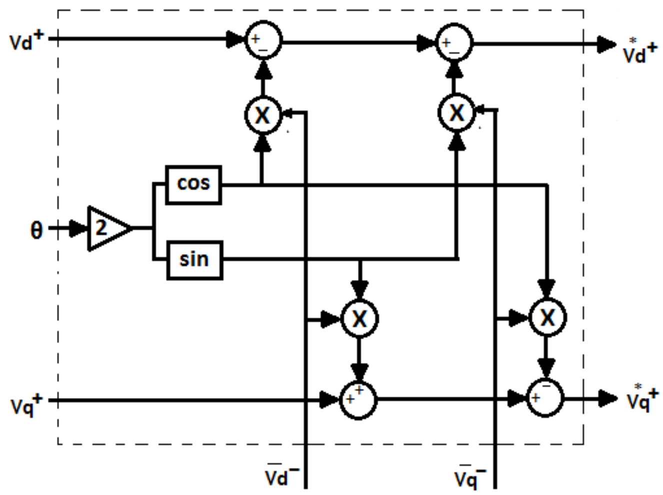
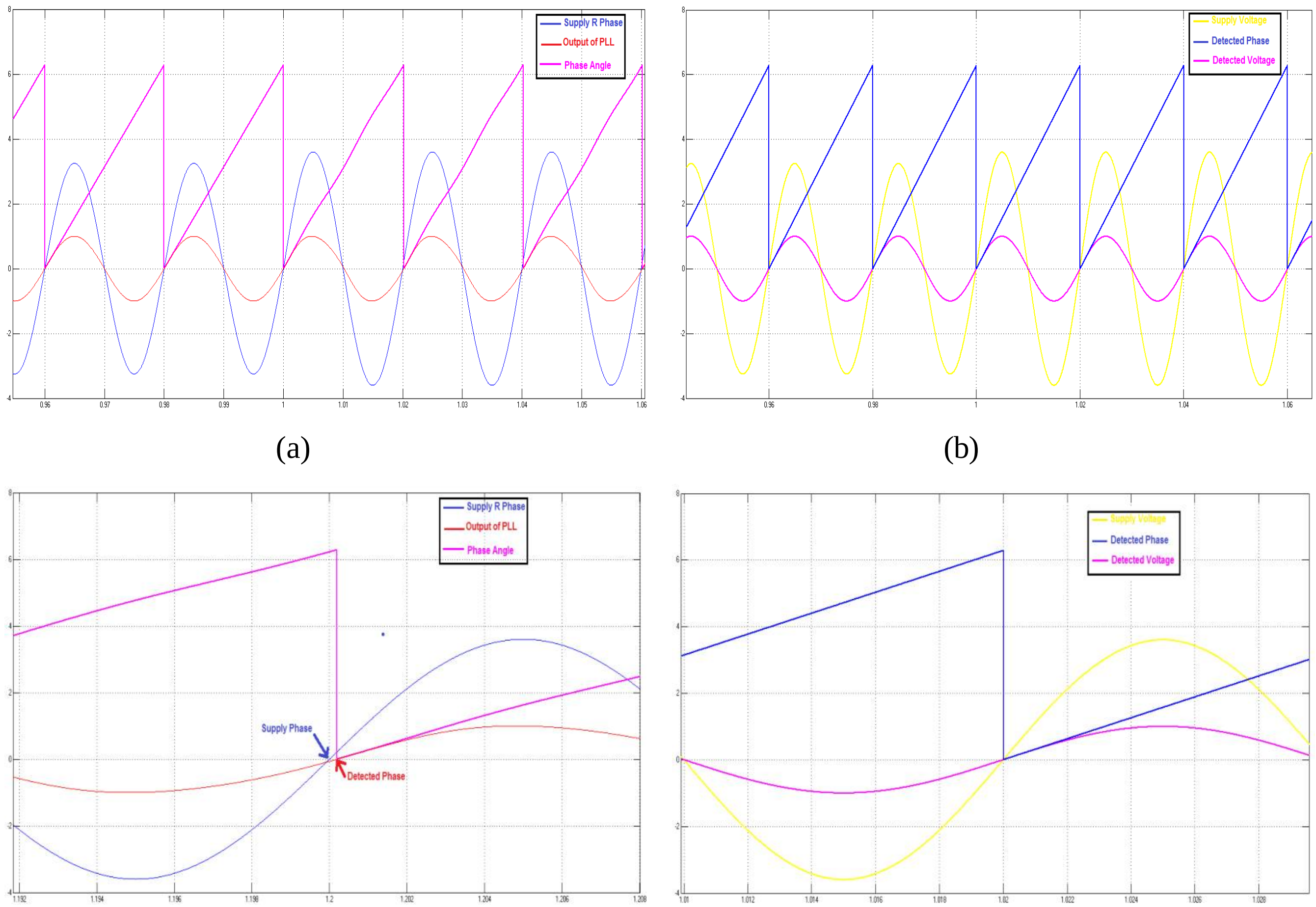


Fig.3 Positive Component Decoupling Network

The performance of SRF-PLL and DSRF-PLL is tested with MATLB simulation and found that when unbalanced condition of voltage is applied, DSRF-PLL has given precise detection of phase while in SRF-PLL its phase detection got deteriorated. In the result presented here a step change in grid voltage is applied after one second simulation time and thus in all results before one second time balanced condition of grid voltage and on other side unbalanced condition of grid voltage is presented. Fig.4 shows the simulation results of SRF-PLL and DSRF-PLL with and without unbalanced voltage applied in grid voltage. From the result it is observed that DSRF-PLL can give better phase detection even in unbalanced voltage condition.



(a) (b)

(c) (d)

Fig.4 In (a) Supply voltage of A phase, θ and voltage with detected phase for SRF-PLL (b) Supply voltage of A phase, θ and voltage with detected phase for DSRF-PLL (c) Zoom view of (a), and (d) Zoom view of (b)

However in weak grid condition DSRF-PLL is not able to synchronize the VSC at stronger PCC to make stable operation because of large impedance drop occurred in grid side impedance which is large due to weaker end of grid. So a virtual impedance block inspired from [29] is developed for DSRF-PLL and added between the sensor signals and DSRF PLL to make it ICDSRF-PLL (Impedance condition DSRF-PLL). Fig. 5 shows the ICDSRF-PLL block diagram. ICDSRF-PLL is tested in MATLAB simulation as well as in experimental set up to obtain its performance and results are presented in fig. 6.

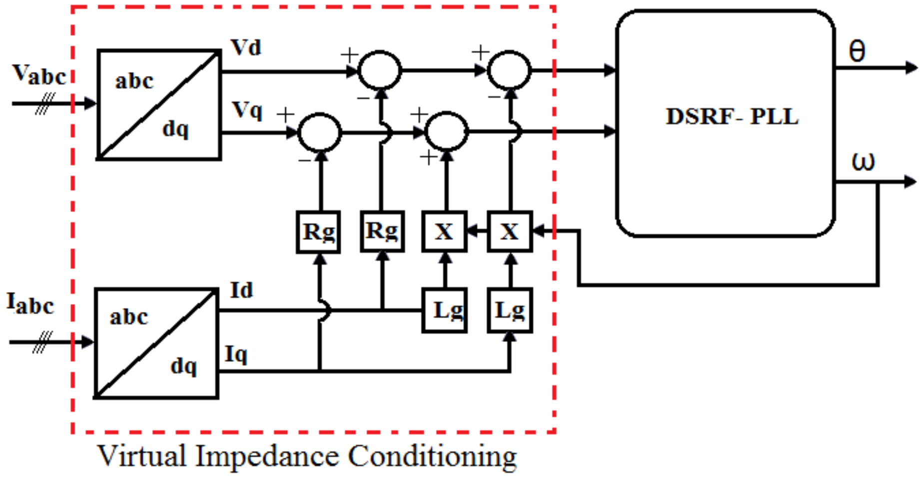


Fig.5. Block diagram of ICDSRF-PLL

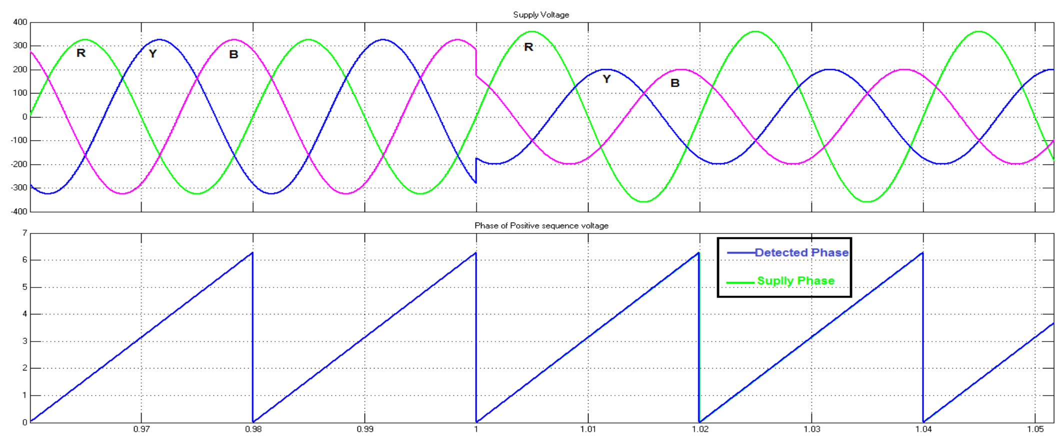
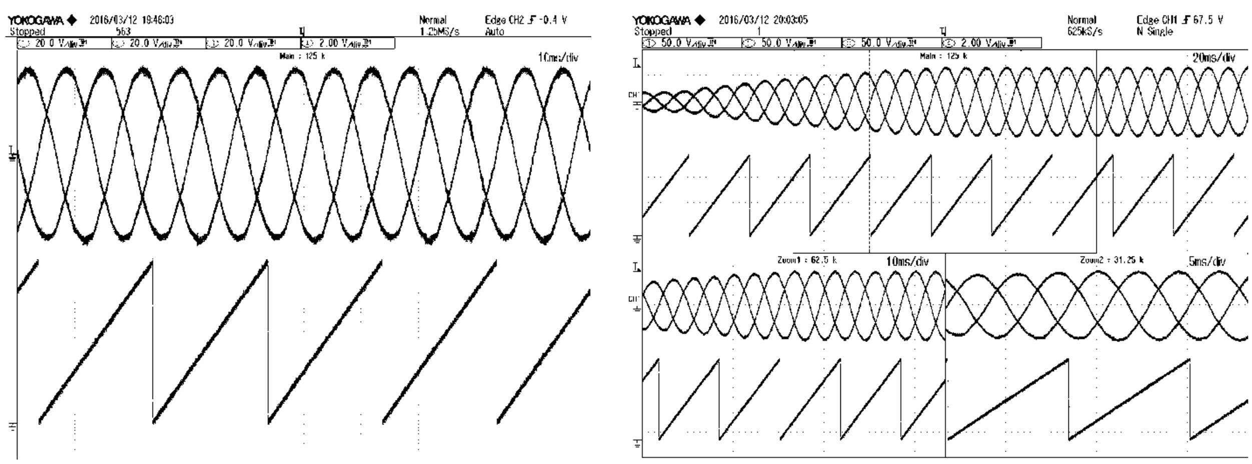


Fig.6 Phase A voltage, θ and Detected Phase voltage of ICDSRF-PLL in Simulation



(a) (b)

Fig. 7 Experimental results of ICDSRF-PLL (a) with normal condition and (b) with voltage fluctuation at PCC

From the simulation and experimental result of ICDSRF-PLL it is found that in weak grid even though effect of voltage drop in grid impedance is large, this technique makes it possible to detect the stronger point of coupling and virtually connect the VSC to that point to achieve stable operation of VSC.

6.1.2 Predictive current controller

Predictive current control offers the advantages of precise current tracking with minimal distortion and can also be fully implemented on a digital platform. In this algorithm Predictive control is used to calculate the necessary converter voltage to optimize the current behavior. Later, a modulator is used to generate this desired voltage. In this control algorithm the switching frequency of converter remains constant as it is a linear control strategy [9]. In predictive current controller if a current error $i_e[k]$ exists at any particular sampled time k, a small correction term is get added to the required phase leg voltage $v_I[k]$ to eliminate this current error for the subsequent time interval $\Delta T[k] = T[k + 1] - T[k]$. Control algorithm implemented for predictive current control with deadbeat condition as

$$i_e[k+1] = \frac{i_e[k] - i_e[k-1]}{2} \qquad (1)$$

This makes controller to operate noise free as it involves averaging of current errors. With this concept, algorithm of predictive current controller established is as

$$V_I[k] = -\frac{1}{2}V_I[k-1] + V_I[k-2] + \frac{1}{2}V_I[k-3] + \frac{L}{\Delta T}\left\{\frac{3}{2}i_e[k-1] - \frac{1}{2}i_e[k-2] - \frac{1}{2}i_e[k-3]\right\} \qquad (2)$$

This predictive current control algorithm is implemented without any parameter transformation as given in fig.8

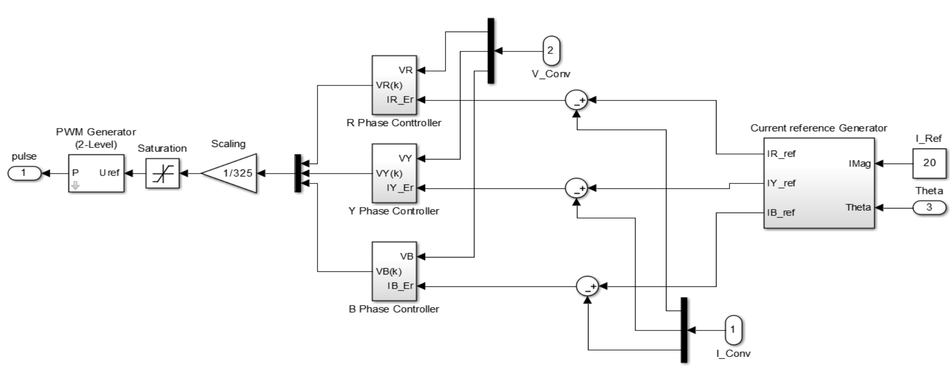
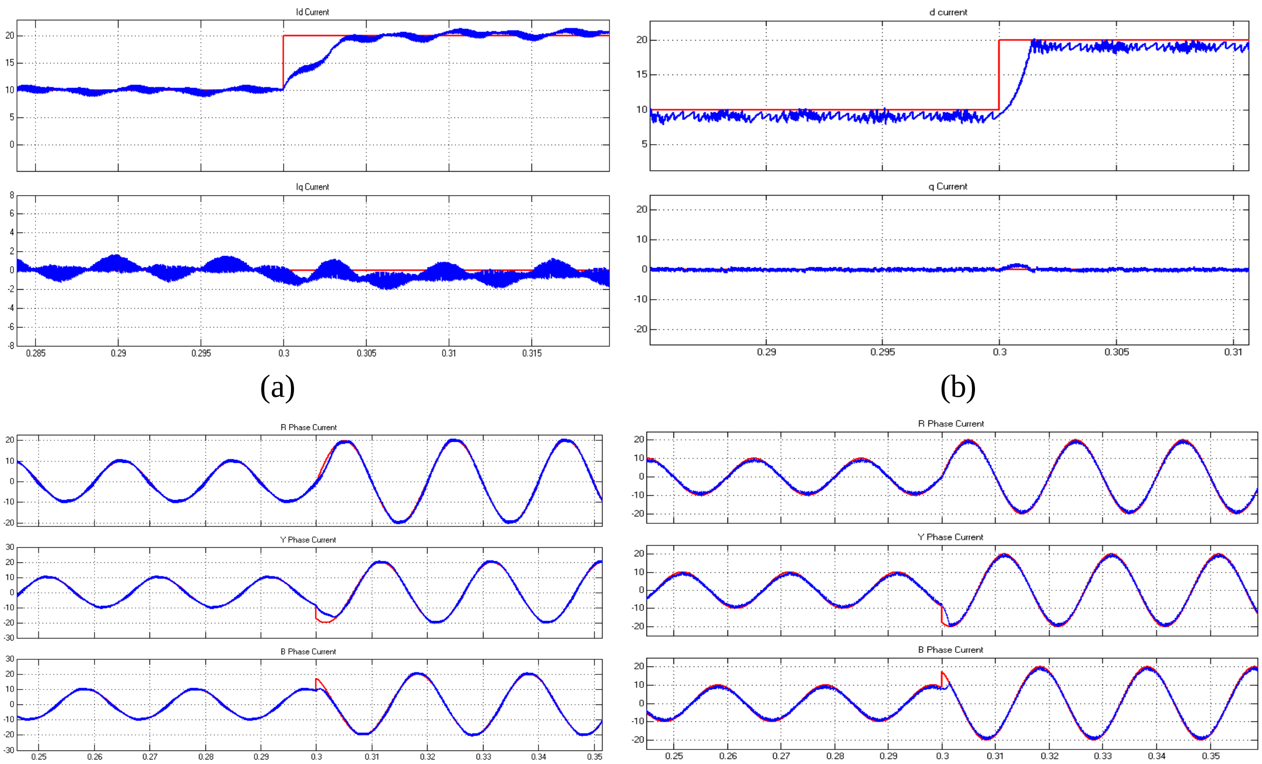


Fig.8 Matlab block of Predictive current control mechanism

Performance of predictive current controller in ABC reference frame implemented as above is tested for dynamic response in MATLAB and results are presented here in fig. 9. The predictive controller performance is compare with the conventional and most frequently used PI controller and it is found that the Predictive current controller gives faster dynamic response as well as involves less ripple amplitude in dq current component of VSC current supplied to grid.



(c) (d)

Fig.9 Current control response (a) PI control response in dq component (b) Predictive control response in dq component (c) PI response in ABC frame and (d) Predictive response in ABC frame

6.2 Performance in Weak Grid

Grid connected converter is usually controlled with constant current to feed in to the grid, so it can be represented as constant current source in small signal model used for understanding the power flow behavior of converter. On the other side power grid can be considered as constant voltage source in series with line impedance of grid [33-34]. Impedance based small signal model is shown in fig.10.

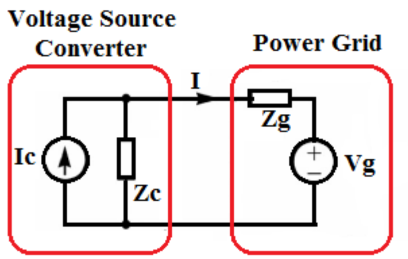


Fig.10. Small Signal Equivalent Grid-Inverter System

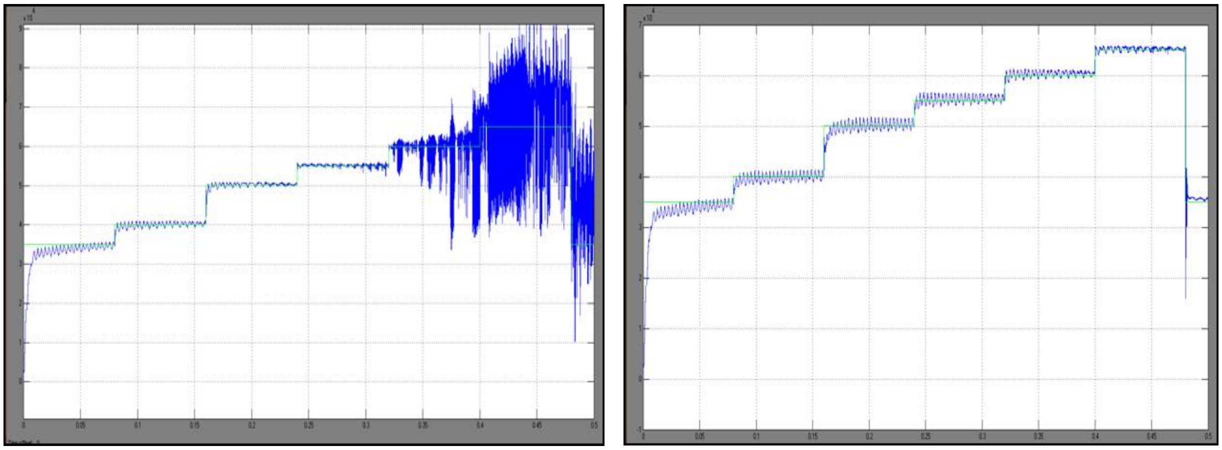
From the equivalent circuit we can have VSC output current as below,

$$I = \frac{I_C Z_C}{Z_C + Z_g} - \frac{V_g}{Z_C + Z_g} \quad (3)$$

By rearranging the terms in equation we can write the converter as,

$$I = \left[Ic - \frac{V_g}{Z_C}\right] \frac{1}{1 + {Z_g}/{Z_C}} \quad (4)$$

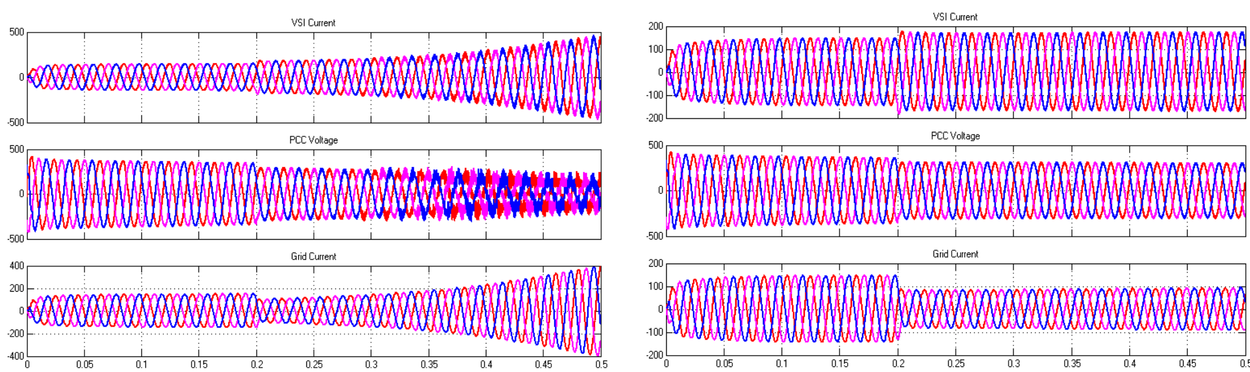
For a stable grid voltage Vg, stability of converter current feed in to the grid is depends on second terms of the equation (4). Hence grid connected VSC can stably supply the current to grid when ratio of grid impedance and converter output impedance satisfy Nyquist criterion of stability which can be achieved when grid impedance is low. But for weak grid condition as the PCC is usually at very far end of Vg, grid impedance will be of a considerable high value. So in weak grid case power transfer from VSC to grid is affected due to high grid impedance. To overcome this issue of weak grid condition as mentioned in previous section in ICDSRF-PLL a virtual impedance conditioning is applied which make VSC connection at stronger PCC of grid and enhances the active power transfer capacity of VSC. This is verified by MATLAB simulation and results are presented in fig. 11. From the response presented it is found that when ICDSRF-PLL which has impedance conditioning term gives stable operation of VSC for larger active power transfer while without impedance compensation converter becomes unstable for higher value of active power.



(a) (b)

Fig.11 (a) Power transfer with SRF-PLL and (b) Power Transfer with ICDSRF-PLL

VSC operation is also tested with local load variation for ICDSRF-PLL by keeping VSC power 50 kW and switching 50 kW local load at PCC. It is found that when VSC is operated with conventional SRF-PLL it becomes unstable to supply power to grid while VSC with ICDSRF-PLL gives stable performance even in transient switching of local load. Both results are presented in fig.12.



(a) (b)

Fig.12 VSC performance with local load switching of 50 kW (a) with SRF-PLL (b) with ICDSRF-PLL

An experimental set up is developed with prototype of VSC connected to grid as shown in fig. 13 below. This setup is tested in grid connected mode by keeping grid side inductor of 3 mH to form weak grid connection of VSC at PCC. dSPACE model 1104 is used to implement real time operation of VSC. Experimental results for various conditions are given in Fig.14 to 16.

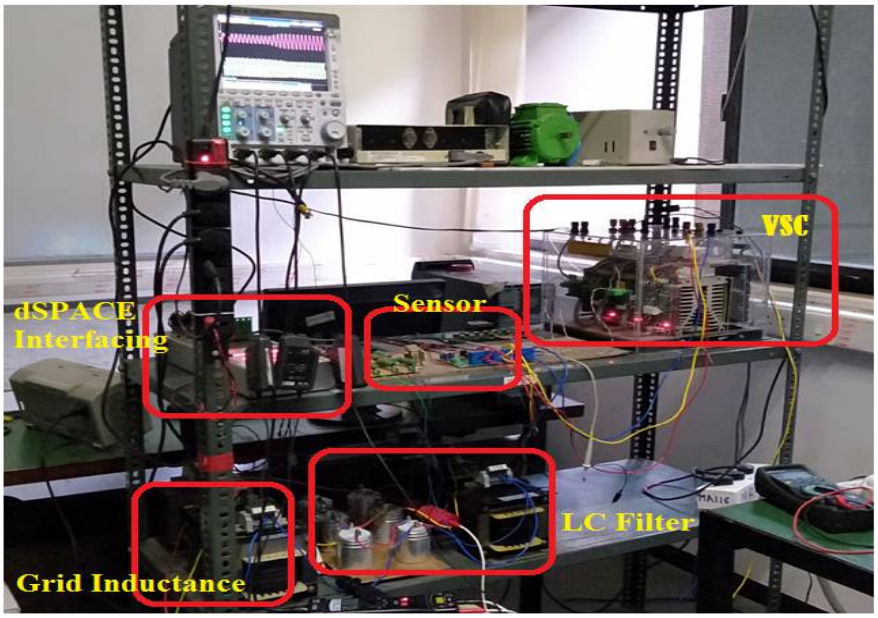


Fig. 13 Experimental Setup for Weak Grid Connected VSC

Table 1: Prototype Parameter

DC Supply	100 Volt
Grid Voltage	70 Volt, 50 Hz
Filter Parameter	4 mH and 25 µF
Grid Impedance	L= 4mH and R=0.1 Ω
Local Load	5 HP

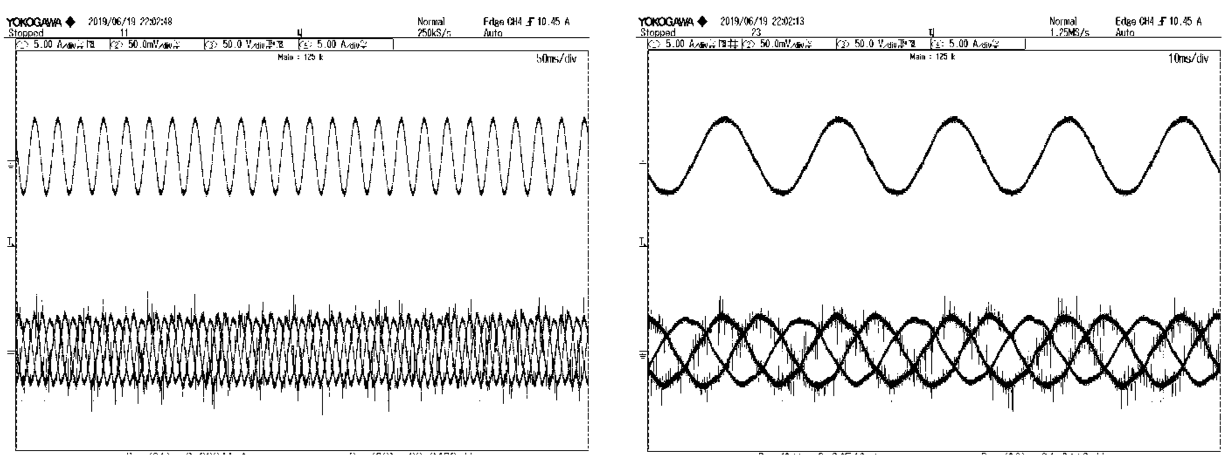


Fig.14. R phase voltage and three phase current

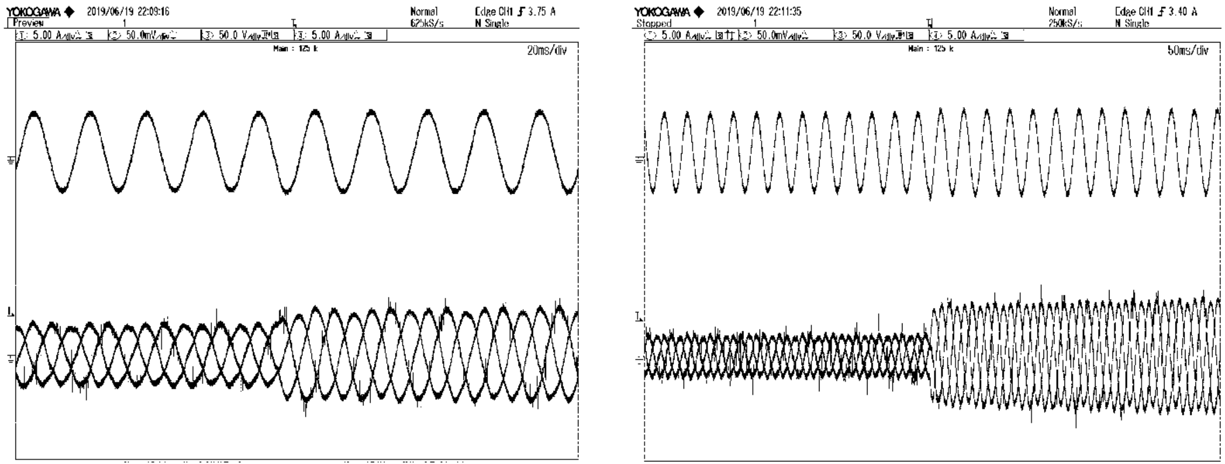


Fig.15. R phase voltage and three phase current for current variation from VSC

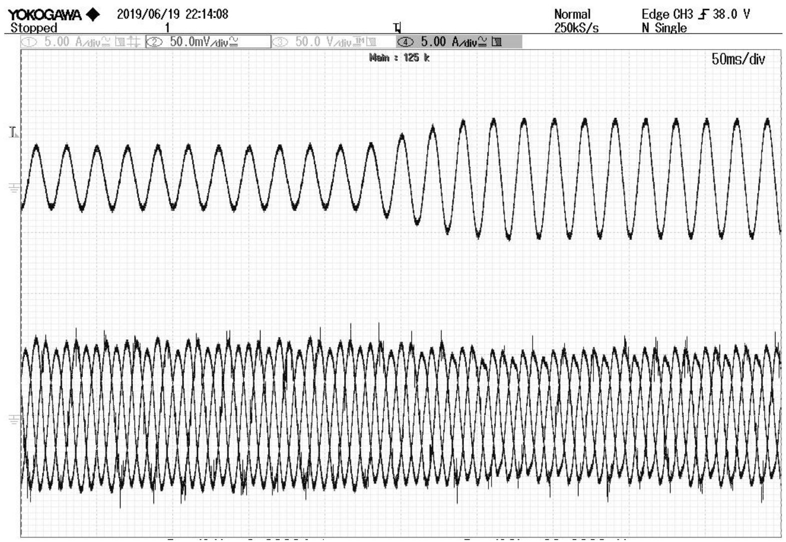


Fig.16. R phase voltage and three phase current for Voltage Variation at PCC

7. Achievements with respect to objectives

In this research with respect to objective stated, following are the remarkable achievements,

- Using simulation techniques, we have verified that large grid side impedance deteriorates the operation of VSC due to error in phase detection by grid synchronization techniques.
- Developed ICDSRF-PLL by combining DSRF-PLL and virtual impedance conditioning term that can overcome the issue of phase detection in weak grid. This newly developed technique has made it possible to synchronize VSC at a stronger virtual PCC of grid. This has enabled us to achieve stable enhanced power transfer from VSC to Grid.

- Implemented predictive current controller in ABC reference frame for grid connected VSC which is simple in implementation on a digital platform and can give fast dynamic response.
- A hardware setup is prepared over which the effectiveness of control structure developed with combination of predictive current controller and ICDSRF-PLL has been tested and found to be consistent with simulation results.

8. Conclusion

After investigating the grid synchronization techniques and control techniques of VSC for weak grid connection it is found that there is an impact of grid impedance on performance of VSC due to its effect on grid synchronization as well as current controller. Also in weak grid condition due to large grid impedance local load switching affects the operation of VSC and power transfer capability of VSC reduces with larger grid side impedance for interconnecting with weak grid. Proposed grid synchronisation technique ICDSRF-PLL developed by combination of Impedance conditioning term and DSRF-PLL makes it possible to synchronise VSC at stronger point in weak grid condition to enhance power transfer capability as well as stable operation of converter. Also, VSC controlled by predictive current control algorithm gives simple implementation with faster dynamic response as well as stable operation of VSC in weak grid conditions.

9. Copies of papers published and a list of all publications arising from the thesis

[1] Atul Kunpara and Dr. Vithal N. Kamat, “A comparative study of grid synchronization technique SRF-PLL and DSRF-PLL under unbalanced grid voltage condition”, International Conference on power control and communication infrastructure 2019.

[2] Atul Kunpara and Dr. Vithal N. Kamat, “The Impact of Grid Impedance in Operation of Voltage Source Converter Integrated to Weak Grid”, International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering Vol. 7, Issue 6, June 2019, ISSN 2321-2004.

Paper in preparation:-

[1] Atul Kunpara and Dr. Vithal N. Kamat, “Active power transfer enhancement of VSC using Impedance Compensated Double Synchronous Reference Frame PLL during weak grid condition”,

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