Operation of Current Controlled Three Phase Grid Connected VSI Under Non-ideal Grid Condition

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Abstract—Power electronics is a subject which deals with efficient processing of electrical power. With depleting fossil fuel reserve, necessity to incorporate renewable energy systems into existing power grid and need of efficient utilisation of electrical energy is growing day by day. A Voltage Source Inverter (VSI) capable of bidirectional power flow has become a basic building block to address such requirements. Generally, control strategies for grid connected VSI have been based on a rich body of research on vector control of motors. Exhaustive work has already been carried out for grid connected VSI focusing on steady state operation under both ideal and non-ideal grid condition. Current trend of research is to meet emerging requirements such as low voltage ride through, behaviour of the power converter during transients etc. In this paper an overview of current controlled three phase VSI has been presented from control point of view. Further the need to meet emerging requirements and design enhancements are indicated.

Index Terms—Three phase four wire VSI, Distributed generation, Fault ride through, Current control, Phase locked loop.

I. INTRODUCTION

In the history of electrical power processing the last few decades have seen the rise of power electronics as an applied subject whose impact has shaped the way electrical energy is used today. In most of the applications a power converter acts as the interface between utility supply and load or between two sources. Physically, a power converter is an interconnection of semiconductor devices and passive components connected in an appropriate manner with control and protection incorporated. The topology or the interconnection depends on application.

At present the electrical power generating stations, such as thermal, hydel and nuclear power plants produce larger share of power compared to renewable energy sources, such as solar, wind, and tidal. To utilize the total capacity with more flexibility these generating units are interconnected to form the power grid. Ideally the grid is considered an infinite source of electrical power whose voltage and frequency remains unchanged irrespective of the loading condition. As establishing newer traditional generating stations are finding increasing limitations due to depleting fossil fuel and possible hazardous impact on environment, recent trend is towards integrating various renewable energy sources to form microgrid structures or connecting them directly at the consumer end at distribution voltage level to inject active power into the grid [1], [2]. Again, applications such as Front End Converter (FEC) for motor drives or UPS demand drawing of active power from grid at unity power factor with low current harmonic distortion level [3]–[7]. Further, applications like Static Compensator or STATCOM [8]–[10], Dynamic Voltage Restorer (DVR) [11] and Active Filter [12] employed for power quality improvement requires bidirectional reactive power flow capability with high bandwidth. An Integrated Gate Bipolar Transistor (IGBT) based bridge connected VSI, as shown in Fig. 1, capable of bidirectional power flow and fast control is a suitable choice for these applications [5]. Current control of grid connected VSI under both ideal and non-ideal conditions are under research for past few decades [13], [14]. Most notable efforts are based on previous understandings on motor control but presence of non-ideal grid condition has led to several modifications [12]–[15]. With growing number of grid connected VSI, new requirements of better performances during transients or short term grid disturbances are emerging and this has become a research topic [16], [17]. Low voltage ride through is one such issue. In meeting such requirements along with the steady state performance, the control architecture needs to be thoroughly scrutinized and restructured. In this paper an overview of current controlled three phase VSI has been presented from control point of view. Some of the research challenges have been highlighted and a few sample experimental results are indicated as possible solutions.

II. GRID CONNECTED VSI

Grid connected VSI’s can be classified into three categories according to their interconnection with utility. Shunt connected inverters, shown in Fig. 2(a), are of current injection type, e.g. STATCOM. Series connected inverters, shown in Fig. 2(b), are of voltage injection type, e.g. Dynamic Voltage Restorer (DVR). Combination of these two, shown in Fig. 2(c), forms the third category, e.g. Unified Power Quality Controller (UPQC). In this paper the focus is restricted to shunt connected VSI, which are typically current controlled.
A. Applications of shunt connected VSI

A list of typical applications of shunt connected VSI which are also indicative of respective steady state requirements is given below.

- Load Compensation
  - Reactive power compensation [9]
  - Harmonic current compensation [12]
  - Unbalance compensation [8]
- Voltage support [10]
- Front End Converter (FEC)
  - Interface for distributed generating sources [1]
  - Interface for motor drives applications [5]–[7]
  - Uninterruptable Power Supply (UPS) [3]–[5]

Hence, the study of the shunt connected VSI topology and its control and enhancement of its reliability is of wide interest.

B. Additional requirements

Apart from meeting desired performance criteria for individual application some additional requirements, listed below, also arise either due to specified regulations or due to ease and efficient transfer of power.

- Availability of neutral wire.
  This requirement arises to cater power to single phase loads or to provide earth fault protection or in a transformerless application [6], [7], [18]. This requirement can be met in following three different ways,
  - Using a \( \Delta - Y \) transformer.
  - Using a four legged inverter.
  - Using the DC bus point of a three legged inverter.
- Injection of harmonic current.
  Active filters are used to cancel the harmonic current drawn by certain load but in general rest of the applications of grid connected VSI’s require very less injected Total Harmonic Distortion (THD) of current. The recommended allowable limit becomes increasingly strict for high frequency current, e.g. according to IEEE guidelines, allowable injection of harmonic current for harmonics of frequency \( > 35^{th} \) in order relative to fundamental is a strict \(< 0.3\% \) [19]. In general VSI’s are connected to grid via \( L \) or \( LC \) filter to reduce the current THD but to meet the stated recommendation a \( LCL \) filter becomes a suitable option. This also increases the level of complexity in controller design.
- Operation under non-ideal grid condition
  Operation of grid connected VSI under ideal grid scenario is a well understood subject. In reality the assumption that the power grid is ideal is not true due to it’s finite capacity and impedance offered by transmission and distribution system. Hence a VSI connected to grid has to work under several non-ideal situations. The non-ideal grid situations can be categorized in following manner.
  - Long duration problem: Non-ideal grid conditions which are almost always or very frequently present in the grid can be termed as long duration problem. Unbalance, frequency variation, presence of harmonics, line notching, voltage flicker are examples.
  - Short duration problem: Transients in grid such as voltage sag and swell, faults in the distribution system, phase jump are unpredictable and generally last for short duration. These types of non-ideal situations can be grouped into short duration problem.

A large transient in the grid voltage can cause sudden changes in DC bus voltage and input current of a grid connected VSI. The VSI may trip rapidly, within the range of few \( \mu s \) to few \( ms \), during grid transient. However, power system protection coordination may require 100s of \( ms \) to few seconds or even longer for operation of protective relays and breakers. Hence it becomes important for a VSI to operate for adequate time even after severe grid disturbances without tripping so that it is available immediately after the fault is cleared.

C. 3 – \( \phi \) 4 wire LCL filter based grid connected inverter

So in all likelihood a 3 – \( \phi \) 4 wire LCL filter based grid connected VSI can be considered as a general module to study different control approaches and overall behaviour of the system under non-ideal grid conditions. Many applications of 3 – \( \phi \) 4 wire grid connected inverter use a \( \Delta - Y \) transformer to supply single phase loads. The \( \Delta - Y \) transformer is used to allow zero sequence currents to flow in lines in one side only. Use of a transformer adds to installation cost and it’s losses increase running cost. Therefore a transformerless approach can be an attractive solution where isolation is not necessary. One of the two available topologies use the midpoint of the DC bus split capacitor as the connecting point for the neutral wire, shown in Fig. 3, and the other one uses a fourth leg for neutral connection. Relative merits and demerits can be found out in references [20] and [21]. In this paper the discussion has been restricted to the topology shown in Fig. 3.
III. CONTROL ARCHITECTURE

Shunt connected VSI’s are generally current controlled. Irrespective of different applications the VSIs interfaced to grid have similar control architecture as shown in Fig. 4. The control principle is based on a two loop strategy where a faster inner current loop is followed by a relatively slow outer voltage loop. The grid synchronization signals are generated by a Phase Locked Loop (PLL) or unit vector generation. Depending on application and to maintain a constant DC bus proper current references are required to be generated. To utilize the DC bus and to achieve lower current harmonic distortion different control strategies can be employed. In depth study of these individual aspects under ideal grid condition have already been carried out by several researchers in recent past. Current trend is to understand the way these individual blocks are affected under non-ideal grid situation and to find suitable methods to overcome the problems. This can pave the way for better control and utilisation of a grid connected VSI under abnormal grid situation.

A. Phase Locked Loop (PLL)

Phase tracking system or PLL is an important part of the control unit of a grid connected power converter. It is used to generate unit sine and cosine signals synchronized to utility voltage in phase and frequency [22], [23]. A PLL can also be used to estimate frequency and voltage magnitude of grid. Popular methods such as zero crossing detection and Synchronous Reference Frame (SRF) PLL do not produce accurate phase information when grid is non-ideal. Constant efforts through last decade by several researchers are going on to find a suitable method to extract positive sequence phase information of fundamental grid voltage [24]–[26]. The proposed solutions are either overtly computation intensive or sluggish in response compared to rapid change in grid voltage during abnormal situations. One such attempt in this field is the Moving Average Filter (MAF) based SRF-PLL [27], shown in Fig. 5. The proposed PLL is capable of working under extreme case of unbalance, such as single line to ground fault, and harmonic rich grid voltage condition. The MAF based SRF-PLL is an improved version of SRF-PLL whose performance deteriorates under unbalanced grid voltage condition due to presence of negative sequence component of voltage.

B. Current control

Objective of controlling line current injected into grid can be summarised as follows.

- Ideal tracking over wide frequency range.
- High dynamic response.
- Constant switching frequency.
- Low harmonic content.
- Capability to work under non-ideal grid condition.

In practice the control strategy contains two cascaded loops. The inner current loop is fast in response. It oversees quality of injected current and protection. The outer voltage loop is
comparably slower in response. It produces part of reference current to control DC link voltage. A number of control strategies have come up over last two decades and all of them perform satisfactorily under ideal grid condition with minor individual merits and demerits [6], [13], [14]. Notable amongst them are listed below.

- Hysteresis current control [13].
- Predictive current control [14].
- Stationary Reference Frame based control [13].
- Synchronous reference frame (SRF) control [12], [15].
- Proportional Resonant (PR) control [14].
- Resistance Emulation Control [6].

Hysteresis current control is the fastest amongst all and independent of parameter variation. Difficulty in input filter design because of variable switching frequency and problems associated with digital implementation are it’s drawbacks. Almost all other techniques result in constant switching frequency. Over the years study on motor control has influenced the control strategies adopted for grid connected VSI. Because of it’s ease in implementation and good steady state performance, SRF control has become a benchmark for all other methods.

1) PLL Less Control: Generally the PLL provides information on magnitude, phase and frequency of grid voltage apart from generating the unit vectors necessary for coordinate transformation and reference calculation. These informations can be utilised for sequence extraction, indication of fault situation and islanding operation. Few control methods such as Resistance emulation control, One cycle control do not require a PLL to generate the references while controlling current at unity power factor. But for enhanced dynamics and stability under four quadrant operation grid voltage information becomes necessary [6], [28].

IV. LOW VOLTAGE RIDE THROUGH

Grid connected inverters often work under a short duration of low voltage condition. This can happen due to turning on of a large load or because of fault. Single phase line to ground faults (SLG) are most common type of fault occurring in a power grid. During such low voltage situation a grid connected VSI can face extreme cases of unbalance voltage. If proper control is not implemented then overcurrent, overvoltage or undervoltage trip may disconnect a VSI from power grid for a neighbouring disturbance. On the contrary if a VSI is able to stay connected to grid during such situation then after the transient it can help the system to restore back to normal operating situation or give supply to a critical load. Recently, regulatory bodies are coming up with regulations for grid connected inverters to have low voltage ride through capability.

These are more strict in case of a renewable energy source such as wind turbine which is to be connected to the existing grid [16], [17].

V. SCOPE FOR STUDY ON GRID CONNECTED VSI OPERATING UNDER NON-IDEAL GRID CONDITION

Almost all the disturbances that occur in grid are seen by the VSI as a disturbance in voltage at the point of common coupling. As non-ideal scenario in power grid can be analysed by sequence decomposition so it can be said that the VSI should be able to work not only with positive sequence component of voltage and current but also with negative and zero sequence components. Though the hardware architecture should be designed to handle such transients but the control architecture poses most critical challenges under non-ideal grid situation. Listed below are few possible interesting areas.

- The PLL which is capable of providing estimation of magnitude, phase and frequency of grid voltage should be fast and less computation intensive. Also it should be capable of indicating different non-ideal situations as and when it occurs.
- In case of a current controller the challenge is to control all the sequence currents. Traditionally used SRF control method needs separate controllers for individual sequence currents to be controlled. A simpler way of implementing control may be in stationary reference frame with predictive or PR control. Again, high bandwidth along with capability to regulate current under fault conditions would be next level of enhancement.
- It is necessary to generate accurate reference current for the current controller to work properly. Particularly during transients such as faults and in post fault scenario a VSI can help supply a critical load or help the system back to normal condition or maintain the DC bus at it’s desired value. Such goals arising in different applications can be achieved when reference generation part is able to switch over to different needs quickly.

VI. EXPERIMENTAL RESULTS

A. Performance of MAF based SRF-PLL under non-ideal grid conditions

1) Operation under unbalanced grid condition: Fig. 6a shows the 3 phase unbalanced voltage signals under which performance of the proposed PLL structure has been examined. Here applied B-phase voltage is 50% of it’s nominal value. The controller parameters are \( K_p = 0.36 \) and \( \tau = 0.08 \text{sec} \). The bandwidth of the proposed PLL is 158 rad/sec. Fig. 6b shows estimation of \( \theta \) along with \( \sin \theta_a \) and \( \cos \theta_e \) during start-up under unbalanced condition. In Fig. 6b the d-axis voltage \( v_d \) which contains 100 Hz component and the output of moving average filter \( v_{af} \) are shown under unbalanced situation. The estimation of frequency is also shown in this figure. The settling time can be observed to be within 3 fundamental cycles.
PLL under distorted grid voltage condition. The results clearly indicate the effectiveness of the proposed performance of MAF based SRF-PLL under distorted voltage as odd harmonic voltages in d and q-axis voltages. To test harmonic voltages, if present in grid voltages, would show up seen as even harmonic voltage in $d$ frame odd harmonic voltages present in grid voltage would be cause of transformation into synchronously rotating reference under fault condition can enhance fault ride through capability of a power converter.

2) Operation under distorted grid voltage condition: Because of transformation into synchronously rotating reference frame odd harmonic voltages present in grid voltage would be seen as even harmonic voltage in $d$ and $q$ axes. Similarly even harmonic voltages, if present in grid voltages, would show up as odd harmonic voltages in $d$ and $q$-axis voltages. To test performance of MAF based SRF-PLL under distorted voltage condition a three phase source was simulated by programming earlier works in stationary reference frame and hence the main for saturation of controller output. PR controller as stated keeps growing in magnitude. If proper anti-windup technique is not adopted then it will result in roll-over of PR digital controller output when the contactor disconnects. Further it may cause a trip when the contactor reconnects. The transfer function of a PR controller is $H(s) = (K_p + \frac{K_i}{s})$. It is capable of giving very high gain at the selected frequency $\omega$. Fig. VI-B shows block diagram of PR controller with anti-windup strategy. A PR controller with anti-windup control was implemented in Altera’s cyclone-II series FPGA with MHz-frequency controller. A PR controller with anti-windup control was implemented in Altera’s cyclone-II series FPGA with MHz-frequency controller. A PR controller with anti-windup control was implemented in Altera’s cyclone-II series FPGA with MHz-frequency controller.

B. Transient disconnection from grid and reconnection

Generally VSI’s are connected to grid by an AC contactor. Sudden fluctuation in grid voltage may result in disconnection followed by immediate reconnection of this contactor. Though such event may last for 100s of ms but the duration is enough for saturation of controller output. PR controller as stated earlier works in stationary reference frame and hence the main input to it is an AC quantity. For a PR controller if error input to controller does not become zero then the sinusoidal output keeps growing in magnitude. If proper anti-windup technique is not adopted then it will result in roll-over of PR digital controller output when the contactor disconnects. Further it may cause a trip when the contactor reconnects. The transfer function of a PR controller is $H(s) = (K_p + \frac{K_i}{s})$. It is capable of giving very high gain at the selected frequency $\omega$. Fig. VI-B shows block diagram of PR controller with anti-windup strategy. A PR controller with anti-windup control was implemented in Altera’s cyclone-II series FPGA with MHz-frequency controller. A PR controller with anti-windup control was implemented in Altera’s cyclone-II series FPGA with MHz-frequency controller. A PR controller with anti-windup control was implemented in Altera’s cyclone-II series FPGA with MHz-frequency controller. A PR controller with anti-windup control was implemented in Altera’s cyclone-II series FPGA with MHz-frequency controller.
clearly indicates the ability of PR controller with anti-windup strategy to reconnect the system.

VII. CONCLUSION
As more and more VSI are getting connected to existing grid to meet our growing energy needs so next level of challenge is to find methods such that the grid connected VSI can safely be utilised during non-ideal grid condition also. In this paper an overview on grid connected current controlled VSI has been presented along with probable scopes for enhancement of it’s operating capabilities. Experimental results of an improved SRF-PLL structure and anti-windup strategy for PR controller show successful steps towards ensuring ride through of grid connected VSI under non-ideal grid condition.

REFERENCES


