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Control of grid Connected Split Source Inverter using Decoupled Control Scheme

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ABSTRACT

The use of an additional boosting stage is mandatory for applications such as fuel cells-based systems, which are characterized by a low and unregulated input voltage. The increasing number of renewable energy sources and distributed generators requires new strategies for the operation and management of the electricity grid in order to maintain or even to improve the power-supply reliability and quality. In addition, liberalization of the grids leads to new management structures, in which trading of energy and power is becoming increasingly important. The power-electronic technology plays an important role in distributed generation and in integration of renewable energy sources into the electrical grid, and it is widely used and rapidly expanding as these applications become more integrated with the grid-based systems. In this thesis, the SSI is controlled by a single parameter, i.e., its dc and ac sides are controlled by the modulation index; it is of paramount importance to investigate its control scheme in grid-connected mode, which has never been studied yet. Models of the SSI dc side and proposes a modified modulation scheme combined with the commonly used synchronous reference frame control technique to achieve a decoupled control scheme of the SSI in grid-connected mode, i.e., the dc and the ac sides of the SSI can be controlled independently, which is convenient for many applications.

Keywords— Decoupled control, grid connected, impedance-based inverters, renewable energy sources (RESs), single-stage, space vector, split-source inverter (SSI), synchronous reference frame, voltage-source inverter (VSI), Z-source inverter (ZSI).

I. INTRODUCTION

Voltage-Source inverters (VSIs) are the most common dc–ac power converters employed in any power electronic system. The VSI embraces only the buck capability with the inversion stage, i.e., the output ac voltage cannot exceed the available dc input voltage. This point is not an issue for many applications with high dc rail. Meanwhile, several applications require the output ac voltage to exceed the input dc voltage. Hence, the use of an additional boosting stage is mandatory for these applications such as fuel cells-based systems, which are characterized by a low and unregulated input voltage.

The increasing number of renewable energy sources and distributed generators requires new strategies for the operation and management of the electricity grid in order to maintain or even to improve the power-supply reliability and quality. In addition, liberalization of the grids leads to new management structures, in which trading of energy and power is becoming increasingly important. The power-electronic technology plays an important role in distributed generation and in integration of renewable energy sources into the electrical grid, and it is widely used and rapidly expanding as these applications become more integrated with the grid-based systems.

During the last few years, power electronics has undergone a fast evolution, which is mainly due to two factors. The first one is the development of fast semiconductor switches that are capable of switching quickly and handling high powers. The second factor is the introduction of real-time computer controllers that can implement advanced and complex control algorithms. These factors together have led to the development of cost-effective and grid-friendly converters.

In the last few years renewable energies have experienced one of the largest growth areas in percentage of over 30 % per year, compared with the growth of coal and lignite energy. Grid-connected wind systems are being developed very quickly and the penetration of wind power (WP) is increasing.

Power converters are the technology that enables the efficient and flexible interconnection of different players (renewable energy generation, energy storage, flexible transmission and controllable loads) to the electric power system. Hence it is possible to foresee how the synchronous machine has a central role in the centralized power system and the grid converter, also denoted as the ‘synchronous converter’, will be a major player in a future power system based on smart grid technologies. While the electromagnetic field has a major role in the synchronous machine, the grid converter is based mainly on semiconductor technology and signal processing but its connection filter, where the inductor is dominant, still has a crucial role to play in transient behavior.

The increase in the power that needs to be managed by the distributed generation systems leads to the use of more voltage levels, leading to more complex structures based on a single cell converter (like neutral point clamped multilevel converters) or a multi cell converter (like cascaded H-bridge or interleaved converters). In the design and control of the grid converter the challenges and opportunities are related to the need to use a lower switching frequency to manage a higher power level as well as to the availability of a more powerful computational device and of more distributed intelligence (e.g. in the sensors and in the PWM drivers).

The PV inverter is the key element of grid-connected PV power systems. The main function is to convert the DC power generated by PV panels into grid-synchronized AC power.

Historically the first grid-connected PV plants were introduced in the 1980s as thyristor based central inverters. The first series-produced transistor-based PV inverter was PV-WR in 1990 by SMA [1]. Since the mid 1990s, IGBT and MOSFET technology has been extensively used for all types of PV inverters except module-integrated ones, where MOSFET technology is dominating. Due to the high cost of solar energy, the PV inverter technology has been driven primarily by efficiency. Thus a very large diversity of PV inverter structures can be seen on the market. In comparison with the motor drive inverters, the PV inverters are more complex in both hardware and functionality. Thus, the need to boost the input voltage, the grid connection filter, grid disconnection relay and DC switch are the most important aspects responsible for increased hardware complexity. Maximum power point tracking, anti-islanding, grid synchronization and data logger are typical functions required for the PV inverters. Actually, in contrast with electrical drive industry, which is 20 years older and driven by cost where the full-bridge topology is acknowledged worldwide, new innovative topologies have recently been developed for PV inverters with the main purpose of increasing the efficiency and reducing the manufacturing cost. As the lifetime of PV panels is typically longer than 20 years, efforts to increase the lifetime of PV inverters are also under way. Today, several manufacturers are offering extended service for 20 years.

Most of the three-phase PV inverters are not typically true three-phase three-wire inverters but rather three-phase four-wire ones. Actually they work as three independent single-phase inverters. Due to the very large variety of transformer less PV inverter topologies, the control structures are also very different. The modulation algorithm has to be specific for each topology. In the following a generic, topology invariant control structure will be presented for a typical transformer less topology with boost stage.

A. Literature Survey

With an imperative demand of reliable and environmentally friendly electricity generation from Renewable Energy Systems (RESs), the total power generation of RESs is continuously booming and is going to be tripled within the next few decade [1]-[4]. Consequently, great efforts have been made by many countries (e.g. Germany, Spain, and Denmark) to introduce more renewable energies such as wind power, Photo Voltaic (PV) power, hydropower, and biomass power, etc. to be integrated into the electric grid. Among various renewable energies, Wind Turbine System (WTS) and PV system technologies are still the most promising technologies, accounting for a large portion of renewable energy generation [4]-[14]. However, the increasing adoption of RESs poses two major challenges, which are in urgent need to be coped with. One is the change of electrical power production from the conventional and fossil-based energy sources to renewable energy resources. The other one is the wide-scale use of power electronics in the power generation, the power transmission, distribution and the end-user application. The power electronics systems should be highly efficient and exceedingly reliable. As this technology has been the key to the energy conversion from the most emerging renewable energy sources, e.g. WTS and PV systems, it should be able to transfer the renewable energies to the power grid, and capable to exhibit advanced ancillary functions (e.g. Low Voltage Ride-Through, L VRT, grid support with reactive power injection). A wide-scale adoption of power electronics technology makes those completely weather-based energies more controllable, but increasingly intricate. Underpinned by intelligent control strategies, the power electronics technology can fulfill the requirements imposed by the distribution, transmission system operators as well as specific demands from the end-customers, especially when more advanced power devices and more accurate knowledge of the mission profiles are available.

Distributed generation (DG) has been gaining increasing attention in recent times. Among widely used DGs are wind turbines, gas turbines, fuel cells and solar cells. Generally, these sources are connected to the grid through inverters and the main function of the inverters is to deliver active power to the grid. Usually, they are operated at unity power factor but some of the systems are designed to inject or absorb reactive power. However, DG systems may not supply power to the grid continuously due to many factors like the unavailability of source and demand and price considerations. In such scenarios, the inverter used in power conversion has some unused capacity. This could be used to provide certain ancillary functions like harmonic and unbalance mitigation of the power distribution system [1]. The advantage of this approach is that a distribution-network operator who has serious power quality problems can rely on the capabilities of DG systems to provide solutions to such problems rather than implementing expensive tailor-made solutions.

Present day power consumers face numerous power quality problems. Among them are harmonics and unbalances which are of great concern. With tremendous increase of nonlinear loads connected at distribution level and with their concerted action of drawing nonlinear currents, such loads cause deterioration of voltage quality [1]–[4]. This may lead to malfunctioning of sensitive loads. The regulatory bodies have specified acceptable harmonic levels that are allowed into grids and harmonic levels that have to be maintained by the utilities.

DG systems are still not widely used for ancillary functions in power distribution systems. With the implementation of flexible DG systems, it would indeed be possible to have integrated functions like harmonic and unbalance mitigation and zero-sequence component suppression schemes embedded in DG control systems. New trends in power electronic converter systems make the implementation of such multiple functions increasingly feasible [1]–[4]. Having identified such possibilities, the main theme of this thesis is to exploit the remaining capacity of DG power converter systems, and reduce the cost of installing dedicated units for carrying out ancillary services. Particularly, in the distribution level, it may not be economical to have dedicated systems to handle such ancillary services.

II. PROBLEM FORMULATION

The diffusion of different renewable energy sources (RESs) into the power system is continuously increasing, in which the role of power electronics technology in the employed power conditioning stage is of paramount importance to fulfill several requirements [1]–[3]. Such requirements vary from the input side, i.e., the RES, to the output side, i.e., the power grid. For the input side, the control of the RES operating point and the regulation of its output voltage are mandatory issues to be considered due to their dependence on the varying climate conditions [4],[5]. Meanwhile, for the output side, specific control schemes are implemented to comply with the standards requirements, e.g., the low harmonic contents of the injected line current [6]. During the last few years, single-stage power conversion systems has undergone a fast evolution to replace the conventional two-stage architecture, which includes a front-end dc–dc boost converter (BC) and an output voltage-source inverter (VSI) [7], [8]. This evolution has grown up to improve the overall system performance in terms of reducing its size, weight, and complexity.

Most of these single-stage topologies and their different modulation schemes have been reviewed in [1], [8], and [9]. Several research works have been done on the SSI, as in [10]–[13], where Abdelhakim et al. [10]–[12] discussed its three-level operation using the diode-clamped and flying capacitors bridges, whereas its single-phase operation is discussed in [13]. Meanwhile, its control scheme in grid-connected mode of operation has not been investigated yet. The SSI is modulated using the same eight standard states of the VSI, unlike the ZSI that utilizes an additional state, called the shoot-through state, to achieve the boosting capability. Such additional state gives an additional degree of freedom to control its dc side independently from the ac one as discussed in [14]–[16], in which the two-stage conventional control method is utilized.

Hence, it is of paramount importance to investigate the possibility of using the conventional synchronous reference frame control technique that is commonly used with the two-stage architecture, with the so-called SSI, which is convenient for many applications. Accordingly, this thesis models the SSI dc side and proposes a modified modulation scheme combined with the synchronous reference frame control technique to achieve a decoupled control scheme of the SSI in grid-connected mode, i.e., the dc and the ac sides of the SSI can be controlled independently.

In this decoupled control scheme, the common mode term of the ac modulating signals is used to regulate the dc side, leading to an additional degree of freedom of having two control parameters like the two-stage architecture. The control system analysis and investigation of different single-stage topologies in grid-connected mode of operation is significantly increasing for different applications. In [17], the control of the three-phase multilevel quasi-Z-source inverters (qZSIs) in grid-connected mode for photovoltaic systems has been discussed, while in [18]–[20], an energy storage system based on the qZSIs without additional circuitry, taking the advantage of several passive elements without limiting the control system flexibility has been introduced. On the other hand, a controller design for the grid-connected ZSI has been discussed in [21] to improve the power quality of the distribution system. Furthermore, the use of the qZSI as an interlinking converter in a typical ac–dc hybrid microgrid has been investigated in [22], in which its control using the maximum boost approach has been studied. Hence, it was mandatory to introduce such investigation with the SSI to figure out the possibility of using it in grid-connected mode and layout the mandatory design steps to achieve this goal, and, also, highlight the associated limitations with this operation.

In this thesis, the SSI is controlled by a single parameter, i.e., its dc and ac sides are controlled by the modulation index; it is of paramount importance to investigate its control scheme in grid-connected mode, which has never been studied yet. Models of the SSI dc side and proposes a modified modulation scheme combined with the commonly used synchronous reference frame control technique to achieve a decoupled control scheme of the SSI in grid-connected mode, i.e., the dc and the ac sides of the SSI can be controlled independently, which is convenient for many applications. The introduced control scheme is analyzed and simulated using a MATLAB/Simulink and the results are presented.

III. GRID CONNECTED VOLTAGE SOURCE CONVERTER

The main purpose of this section is to introduce the reader to different aspects of a VSC connected to a grid. Furthermore, different types of grid filters and modulation techniques will be presented. Two control principles will be introduced, the voltage angle control and the vector current control principle. Finally, the modeling of the system will be described.

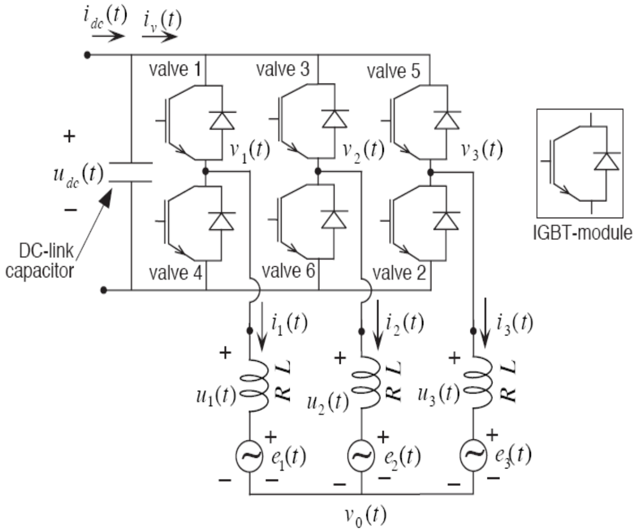


Fig.3.1: The circuit of the VSC

A scheme of the main circuit of the VSC is shown in Figure 3.1. The valves are of the IGBT type. When connecting a VSC to a grid, an inductor must be mounted between the VSC, which is operating as a stiff voltage source, and the grid, which also operates as a stiff voltage source [11]. The simplest and most common grid filter is the L-filter, which has three series connected inductors, one in each phase. The LC-filter has the same series inductors, one in each phase, as the L-filter. In addition, the LC-filter has three parallel coupled capacitors. This filter type has often been supply and in most investigations, the load consists of resistors, one in each phase [12].

When connecting a system with the LC-filter to a public grid, problems can occur due to resonances. The resonance frequency depends on the capacitor value of the filter and the inductance value of the grid, which varies over time. It is difficult to reduce the resonance, because resonance frequency changes with grid inductance and, in addition, the harmonic distortion spectrum of the grid changes with time. The resonance problem can be reduced by using an LCL-filter [13]. The main advantages of using an LCL-filter are low grid current distortion and reactive power production. The resonance frequency can be determined almost independently of the grid configuration. The disadvantage is a more complicated system to control. The L-filter attenuation is a 20 dB/decade and the LCL-filter attenuation is a 60 dB/decade for frequencies over the resonance frequency of the filter. To improve the attenuation of the system when using the L-filter, a tuned shunt filter can be introduced which is tuned to the switching frequency of the VSC [14].

A. Three-Phase Split-Source Inverter (SSI)

Voltage-source inverters (VSIs) are the most common dc–ac power converters employed in any power electronic system. The VSI embraces only the buck capability with the inversion stage, i.e., the output ac voltage cannot exceed the available dc input voltage. This point is not an issue for many applications with high dc rail. Meanwhile, several applications require the output ac voltage to exceed the input dc voltage. Hence, the use of an additional boosting stage is mandatory for these applications such as fuel cells-based systems, which are characterized by a low and unregulated input voltage. Recently, dc–ac power converters which embrace the buck boost capability in a single stage are gaining attention due to their merits compared to the two-stage equivalent in terms of size, cost, weight, and complexity of the whole system.

The most common topology in this power converter category is the conventional Z-source inverter (ZSI) topology, exploits an impedance network that comprises four passive elements in addition to a diode that carries the full power to work as a buck-boost stage. Several topologies exist for the so-called ZSI in addition to the conventional one; among them the quasi ZSI (qZSI) and the current fed qZSI are introduced. Other topologies like the switched-inductor ZSI and the switched-inductor qZSI are discussed. Moreover, the semi ZSI is another ZSI topology introduced as a low cost solution for single-phase photo-voltaic systems.

The conventional topology having the disadvantage includes Complexity and the Output ac voltage cannot exceed the available dc input voltage. ZSI requires an additional switching state out of the conventional eight states, besides having a discontinuous input current and utilizing four passive elements. Hence, this thesis proposes a different topology called the split-source inverter (SSI). This topology utilizes a reduced passive element count compared with the ZSI, in addition to a diode for each inverter leg. The advantages of the proposed topology, compared with the ZSI, are: a continuous input current, a standard modulation strategy that employs the same eight states of the VSI, and a constant inverter voltage with a low frequency component. This topology is derived by integrating a boost converter into a three-phase VSI, by connecting the boost inductor to the switching nodes of the inverter legs via diodes. The employment of the boost converter in dc–ac power conversion was first studied, where studies the possibility of making a combination from two boost converters to get a sinusoidal output voltage. The possibility of eliminating the boost converter semiconductor active switch is by utilizing the lower semiconductor active switch of a single-phase VSI for power factor correction application.

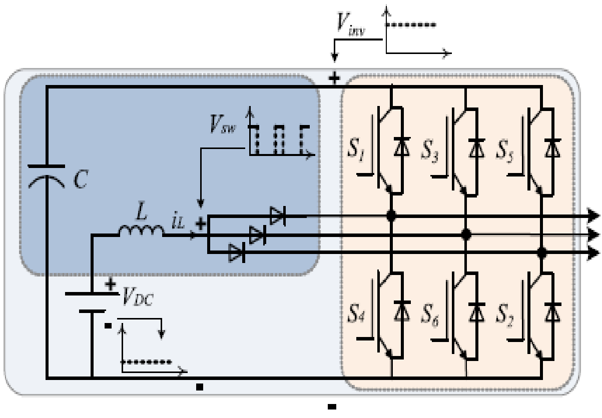


Fig.3.2: Split source Inverter

The merits of split source inverter include the continuous input current, Power factor correction and Constant inverter voltage with a low frequency component.

The applications of the above inverter are with high dc rail and fuel cell based systems.

IV. SIMULATION RESULTS

This Chapter presents detailed simulation results of the proposed control system. The simulated system is shown in Fig. 4.1. Simulation studies are carried out in the MATLAB/SIMULINK environment.

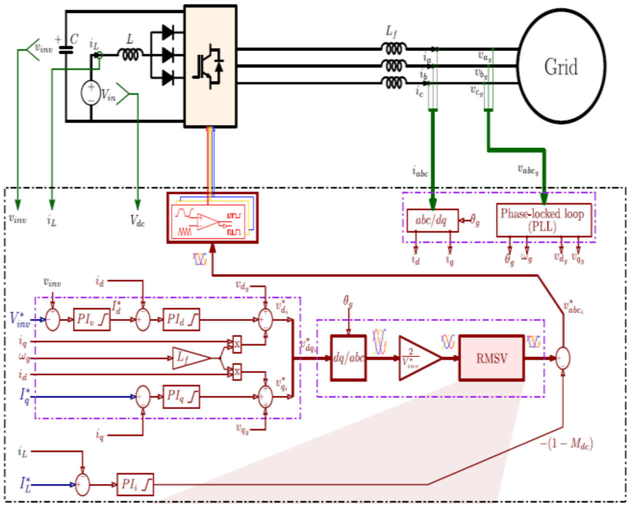


Fig.4.1: Proposed topology

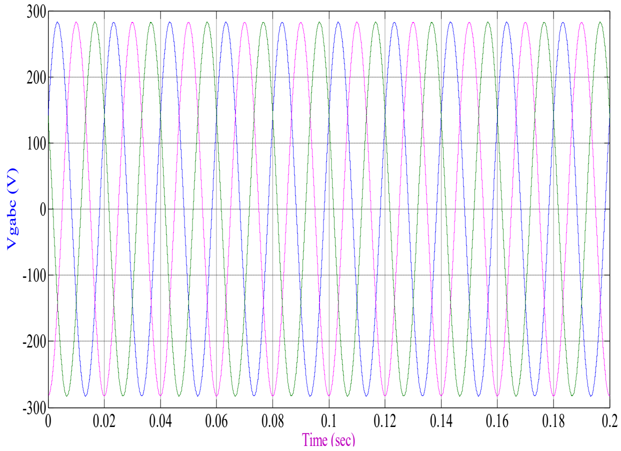
Table 4.1: Simulation parameters

S. No.	Parameter	Value
1.	Filter inductance	4.3mH
2.	Inverter Voltage	425V
3.	Filter resistance	1.3 ohm
4.	Grid frequency	50Hz
5.	Capacitance	120 micro farad
6.	Inductance	1.7 mH

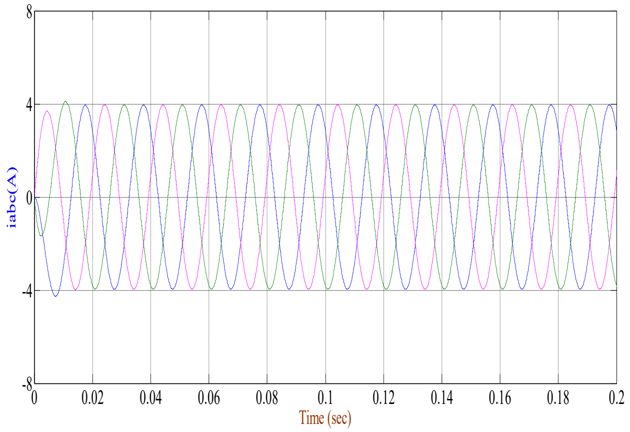
The control scheme has been designed and the different PI controllers are designed considering a bandwidth of 500 Hz for the output current and input current control loops (i.e., for PId , PIq , and PIi), and 50 Hz for the dc-link voltage control loop (i.e., for PIv). It is worth noting that the bandwidth of the dc-link voltage control loop is much higher than the practical value, which has been chosen to figure out the limit of the proposed control scheme. The parameters of the different PI controllers are as follows: The proportional and integral gains equal 13.3 and 8080, respectively, for the output current controllers, 0.0648 and 5.93, respectively, for the dclink voltage controller, and 0.0129 and 3.98, respectively, for the input current controller.

Using the designed parameters in Table 5.1, a MATLAB/Simulink model has been implemented to test the proposed control scheme. The steady-state simulation results of this model are shown in Fig. 5.2 during the normal system conditions (i.e., rated input current and nominal grid voltage), where the grid line-to-line voltages v_{gabc}, the inverter output currents i_{abc} , the dc-link voltage v_{inv}, and the input current i_L are shown for one fundamental cycle.

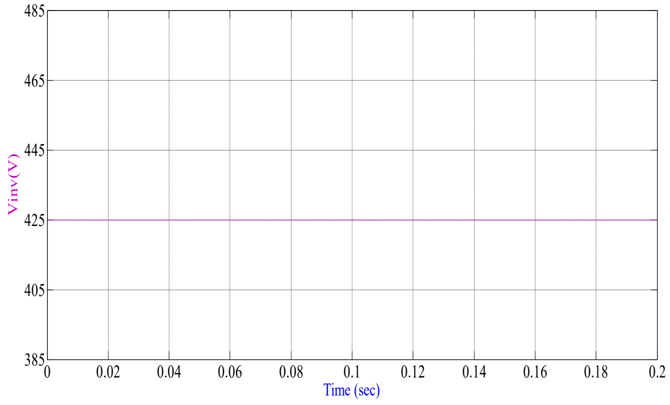
This MATLAB/Simulink model is used again to test the proposed control scheme considering different transients. The considered transients are as follows: a step variation in the input current reference as shown in Fig.5.3, a grid voltage swell of 15% for five fundamental cycles are shown in Fig.5.4, and a grid voltage sag of 15% for five fundamental cycles as well is shown in Fig.5.5. Finally, Fig. 5.6 shows the same simulation results introduced in Fig. 5.2 but considering a grid voltage swell of 23%, which is higher than the designed maximum limit. According to these shown simulation results, the regulation index and the modulation index are independently controlled. Hence, a complete decoupled control of the two parameters is achieved and the possibility of controlling the SSI using the two-stage control scheme has been proved under the proposed control scheme.



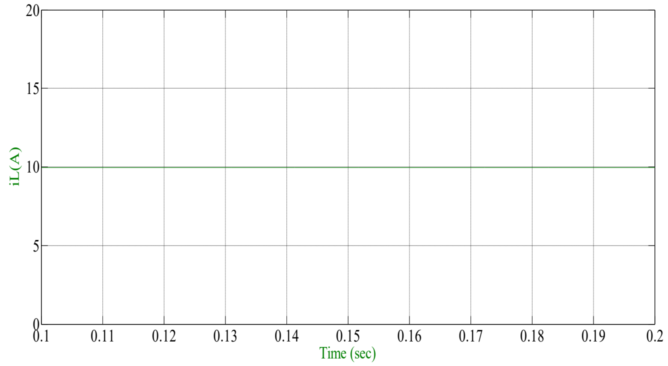
(a) Grid Voltage



(b) The inverter output currents

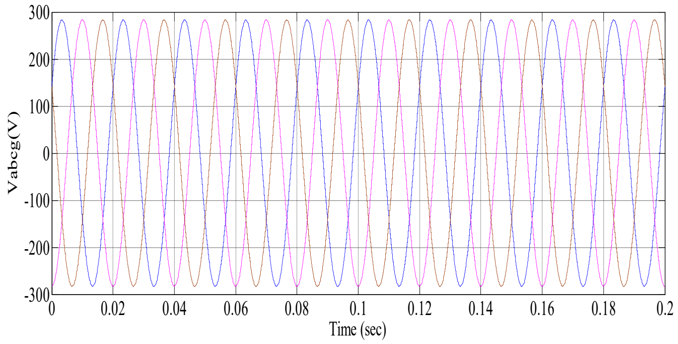


(c) The dc link voltage, Vinv

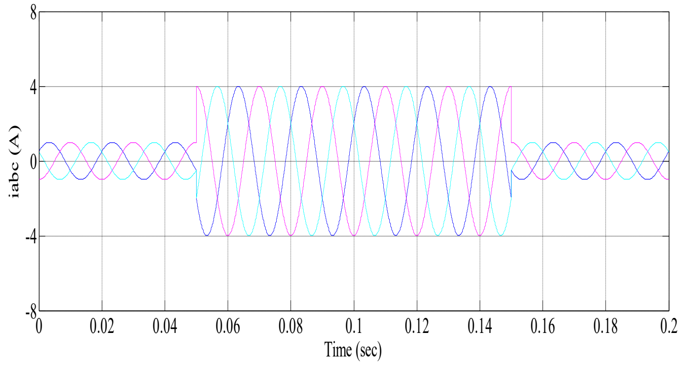


(d) Input current, i_L

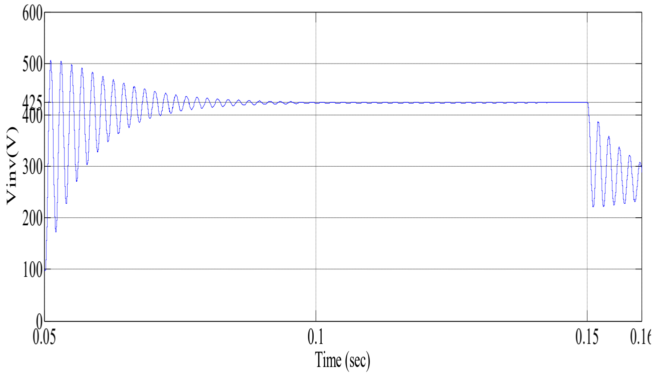
Fig.4.2: Grid-connected SSI simulation results at steady-state



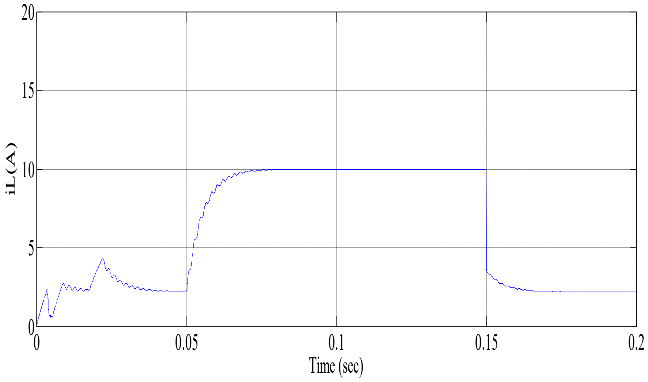
(a) Grid Voltage



(b) The inverter output currents

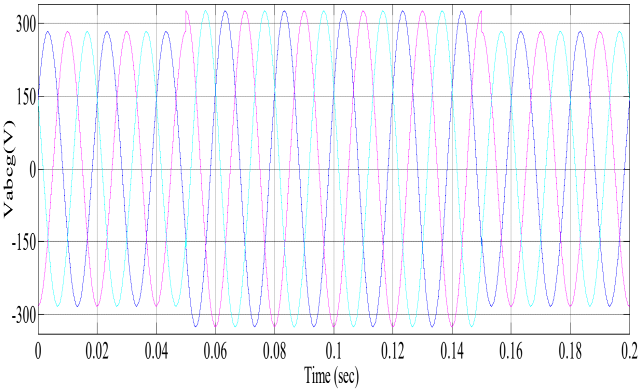


(c) The dc link voltage, Vinv

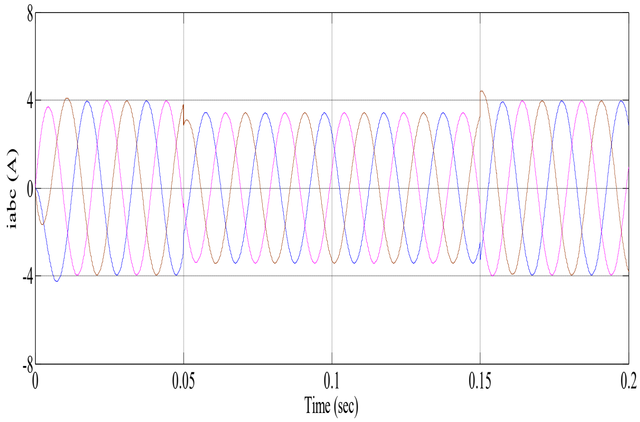


(d) Input current, i_L

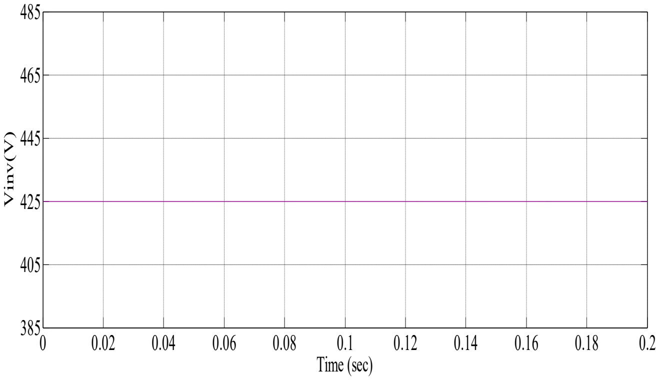
Fig.4.3: A step variation in the input current



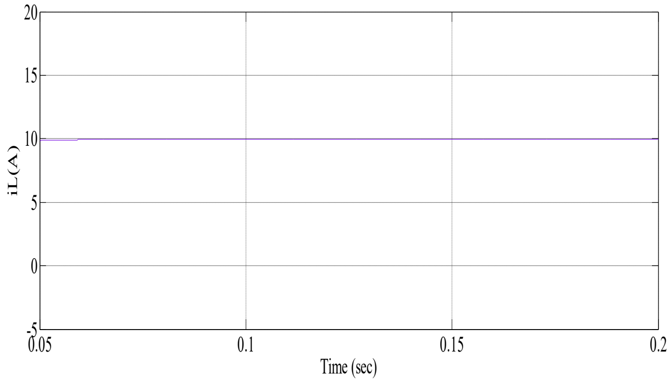
(a) Grid Voltage



(b) The inverter output currents

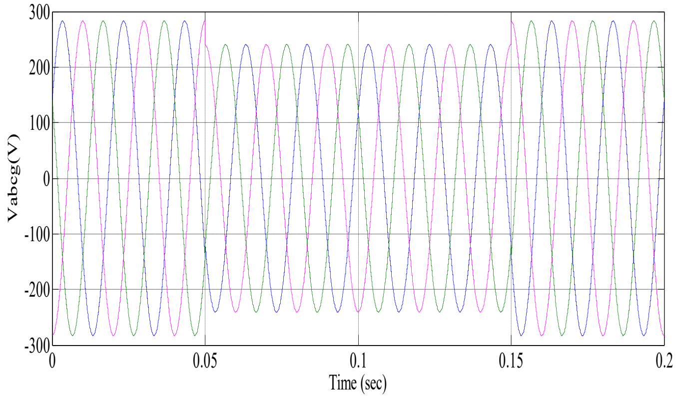


(c) The dc link voltage, Vinv

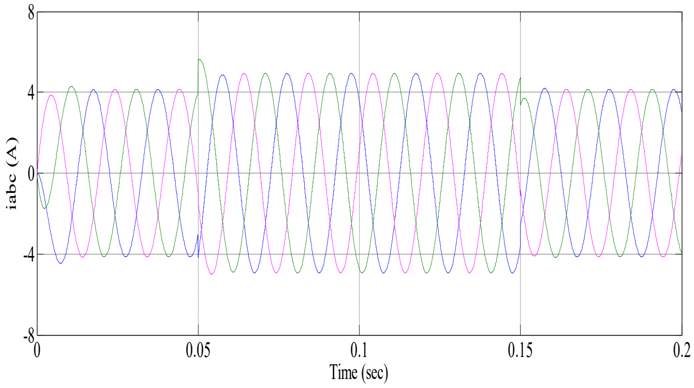


(d) Input current, i_L

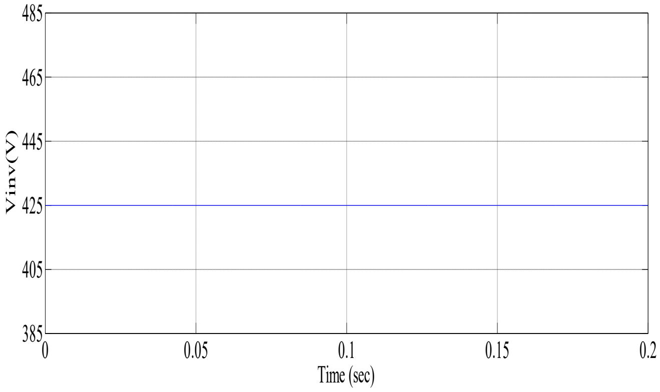
Fig.4.4: Grid voltages swell of 15%



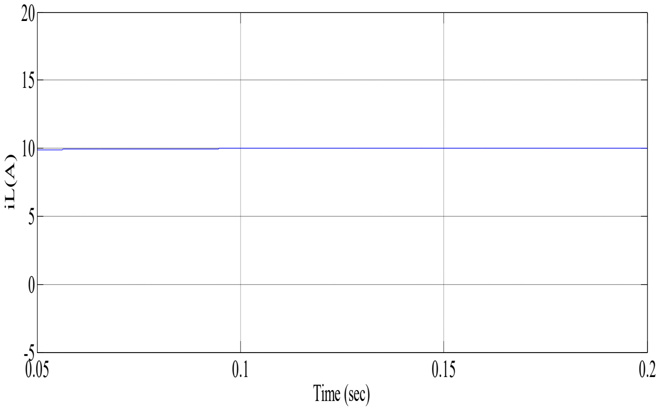
(a) Grid Voltage



(b) The inverter output currents

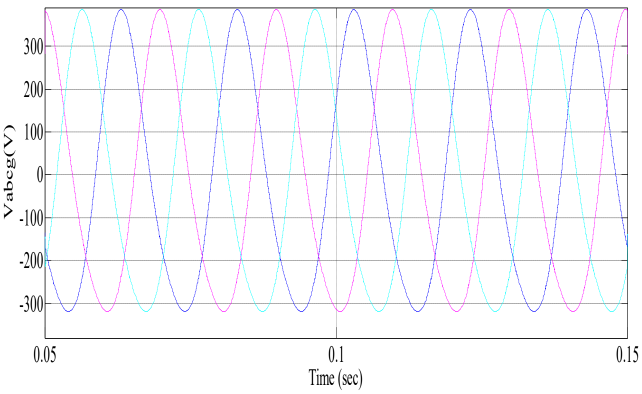


(c) The dc link voltage, Vinv

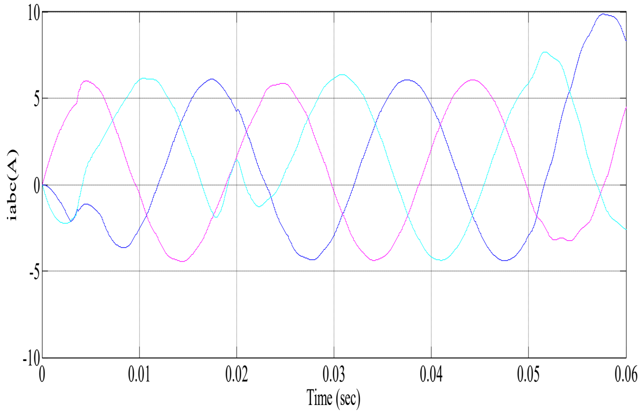


(d) Input current, i_L

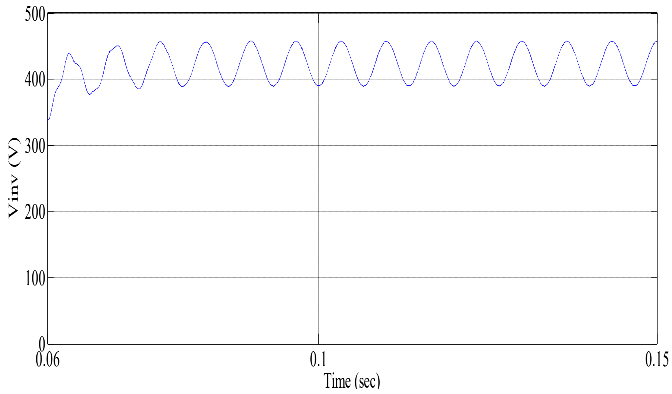
Fig.4.5: Grid voltages sag of 15%



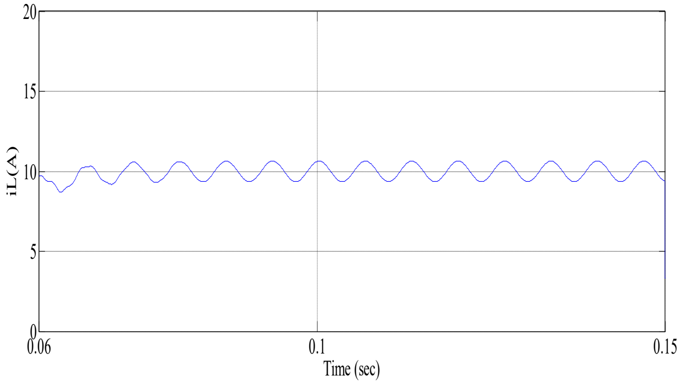
(a) Grid Voltage



(b) The inverter output currents



(c) The dc link voltage, Vinv



(d) Input current, i_L

Fig.4.6: A grid voltage of 23% to show the saturation effect

V. CONCLUSION

In this thesis, the closed-loop control of the SSI in grid connected operating mode was addressed, and a decoupled control scheme was introduced to independently control the SSI dc and ac sides, which is convenient for many applications. This control scheme is based on a combination of the proposed RMSV modulation scheme and the commonly used synchronous reference frame control technique. The SSI dc side was modeled first and then the introduced control scheme was discussed. This proposed work tested the introduced control scheme using MATLAB/Simulink model, considering different transients, and then verified the simulation. As discussed in the simulation results, the system is properly controlled and a fully decoupled control of both the input dc current and the output ac current was achieved.

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