

Modelling and Control of Grid Connected Split Source Inverter Using Decoupled Control Scheme

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Abstract:

Grid-connected power conversion systems for renewable energy sources must fulfill several requirements, e.g., the high efficiency, the reduced cost and complexity, and, quite often, the boost capabilities that is usually achieved using a front-end dc-dc boost converter before the inversion stage, leading to a two-stage architecture. Meanwhile, single-stage power conversion systems, which perform the boosting operation within the inversion one, offer some potential advantages, in terms of reducing the complexity and the volume of the whole system. Among several proposed options, the split-source inverter (SSI) has been recently proposed by Abdelhakim *et al.* as an alternative option with some interesting features to the commonly used Z-source inverter. Taking into account that 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. Hence, this paper models 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 model, where a reduced scale 1-kVA grid-connected SSI is designed and simulated for the sake of experimental validation. Finally, the designed system is implemented experimentally to validate and verify the reported analysis and simulations.

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.

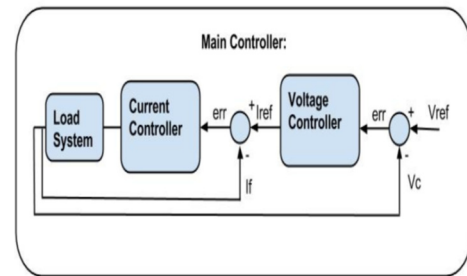
The increase in the power that needs to be managed by the distributed generation systems leads to the use of more voltage levels, leading to more complex structures based on a single cell converter (like neutral point clamped multilevel converters) or a multi cell converter (like cascaded H-bridge or 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.

OVERVIEW OF CONTROL STRUCTURE



It is common to use an inner CCL to regulate the converter current and an outer VCL to regulate the converter voltage output. Cascaded control requires that the bandwidth (speed of response) increase towards the inner loop, with the CCL being faster than the VCL [27]. In certain control strategy, power control loop (PCL) is added in order to control the power delivered to the grid.

In a cascaded control structure the inner control loop has the vital role in the overall dynamic responsiveness. Thus optimal performance of CCL has been the main focus in the present control schemes development

Types of Controller

Various types of controller exist in the industry; however hysteresis controller and proportional integral (PI) controller are the most commonly used controller and further discussed below.

Hysteresis Controller

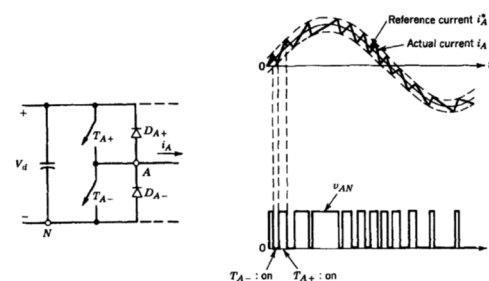


Fig: Hysteresis current control

Hysteresis control or sometimes named tolerance band control for current regulator can be traced in power electronic book by Ned Mohan [35]. Figure 3.1 below shows a sinusoidal reference current with an upper and lower band limit which forms the tolerance band. It can be seen that when the actual current reaches the upper band limit, TA- switch is turned on (TA+ switch is turned off) connecting ground voltage to the load which will lead to reduction of actual current. On the other hand, when the actual current reaches lower band limit, TA+ switch is turned on (TA- switch is turned off), hence delivering voltage V_d to load. It is significantly indicated in the figure below that this method of control results in irregular switching frequency during the fundamental period. The switching frequency is dependent on tolerance bandwidth and the changing rate of actual current

from upper to lower band limit and vice versa. While actual current rate of change is determined by the voltage level V_d and the load impedance.

However due to its fast response, hysteresis controller can be a preferable option especially in current control which required a high speed control response. In addition, hysteresis controller has its relatively distinct advantages for its simplicity of implementation and the exclusion from the need of known load parameters in controller design.

Proportional Integral (PI) Controller

PI controller is a linear controller and perhaps one of the most common controllers used in the industrial control system. It works on the principal of control loop feedback as depicted in Fig.4.3. The error of the reference and measured output signal is the function of the control response which will regulate the output until it matches the reference value. There are two terms namely proportional and integral action in the controller.

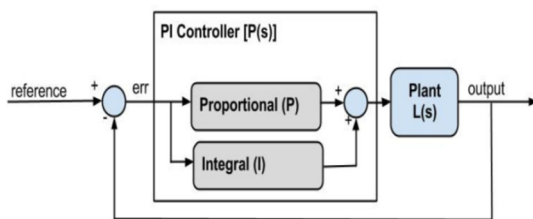


Fig: Generic system structure of PI controller

The control action of the proportional term is simply proportional to the control error. The proportional term output is given by multiplying the error by a constant K_p which is called the proportional gain constant. As the error becomes larger the proportional term output of the controller is magnified to give more correction. A high K_p will produce a large change in output and may lead to system instability while a too low K_p will result in a less responsive controller to the system disturbance [36]. From Fig. 4.3 it can be understood that the proportional term is a timely and fast control however it will result in a small control error in steady state [37].

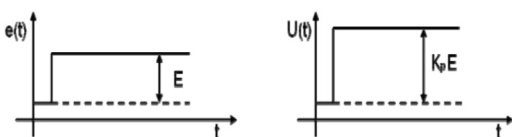


Fig.: Input and output of proportional term control

The main objective of integral term in PI controller is to eliminate control error in steady state. The integral control is proportional to the magnitude and duration of the error. It calculates and accumulates a continuous sum of the

error signal. Thus a small steady state error will result into a large error value over time as shown in Fig.4.4. The accumulated error is then multiplied by constant K_i which is called the integral gain constant and gives the integral control output. A small positive error will always lead to an increasing control output and vice versa [36]. Thus it vividly shows the advantage of integral action in eliminating steady state control error.

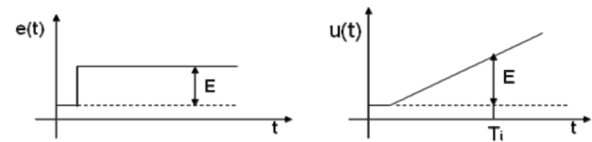


Fig.: Input and output of integral term control

Controller Optimization

Controller design is implementing a specific methodology to determine the parameters of the controller. Parameter of a PI controller in this context consists of the proportional gain constant, K_p and the integral time constant, T_i . Different methodologies applied on the same control system will produce a different dynamic response or more often the term specification of a control system is used. The typical specification of a control system may include attenuation of load disturbances, sensitivity to measurement noise, set-point following and robustness to model uncertainty [36]. Some of the specification of a control system is conflicting with each other, for example attenuation and sensitivity to measurement errors, while some specification may not be relevant to the control system requirement.

SIMULATION RESULTS

This Chapter presents detailed simulation results of the proposed control system. The simulated system is shown in Fig. 5.1. Simulation studies are carried out in the MATLAB/SIMULINK environment.

PROPOSED TOPOLOGY

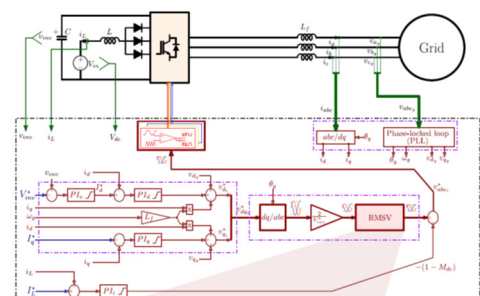


Fig: Proposed topology

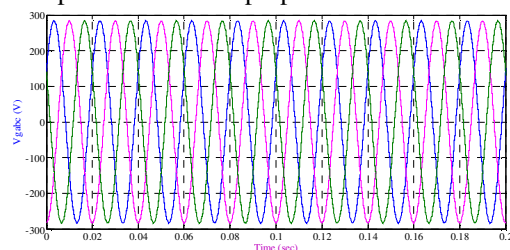
Table: Simulation parameters

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

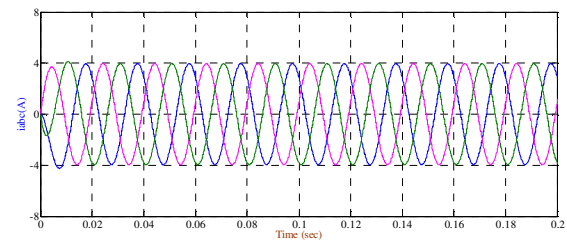
The control scheme has been designed and the different PI controllers are designed considering a bandwidth of 500Hz for the output current and input current control loops (i.e., for PI_d , PI_q , and PI_i), and 50 Hz for the dc-link voltage control loop (i.e., for PI_v). It is worth noting that the bandwidth 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.

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

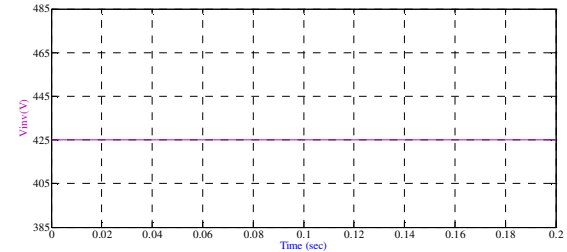
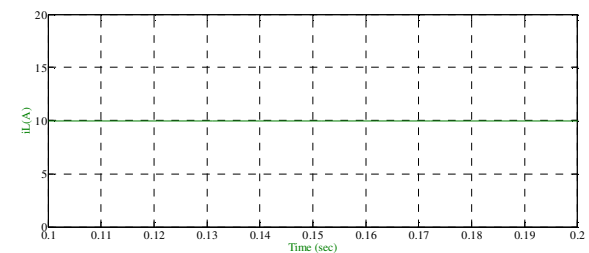
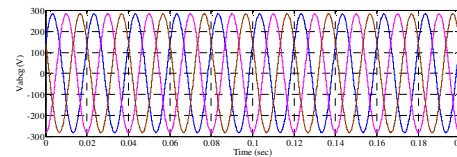
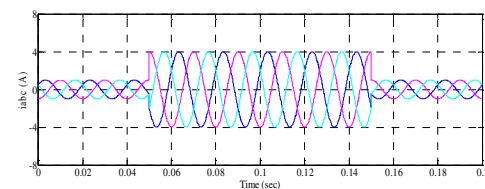
(c) The dc link voltage, V_{inv} (d) Input current, i_L

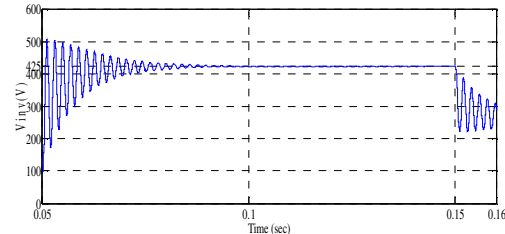
Fig: Grid-connected SSI simulation results at steady-state

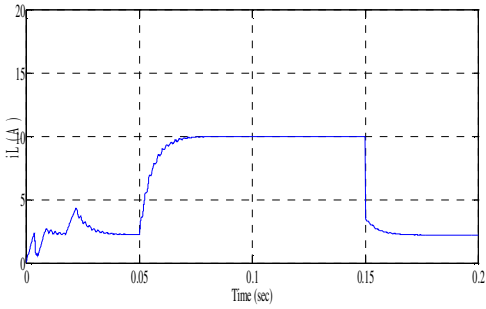


(a) Grid Voltage

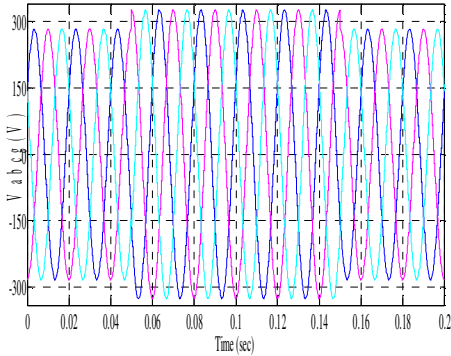


(b) The inverter output currents

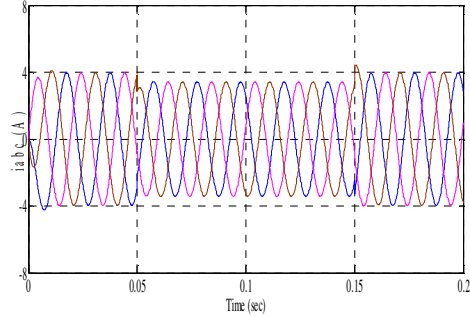
(c) The dc link voltage, V_{inv}



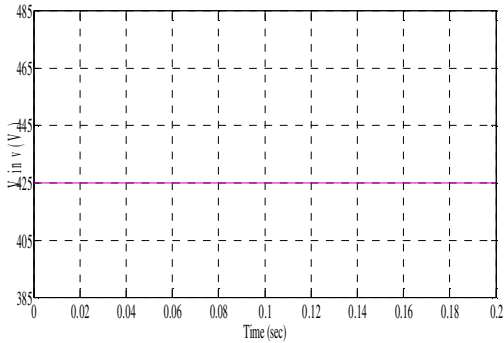
(d) Input current, i_L
Fig: A step variation in the input current



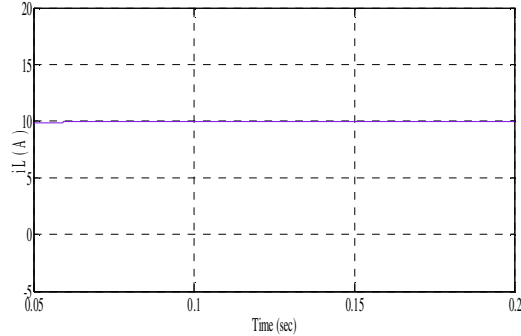
(a) Grid Voltage



(b) The inverter output currents

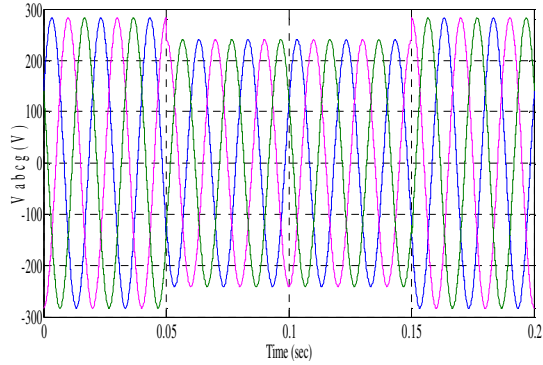


(c) The dc link voltage, V_{inv}

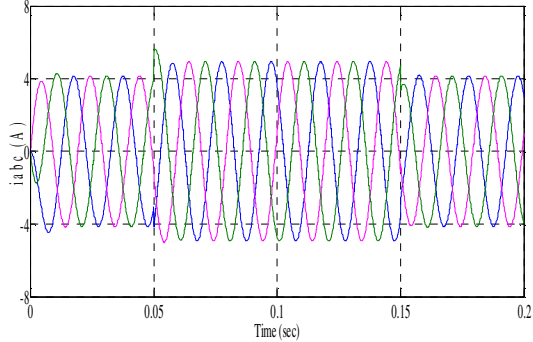


(d) Input current, i_L

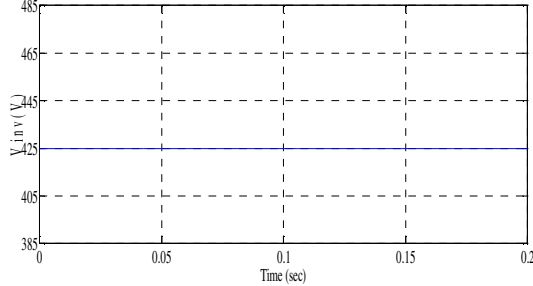
Fig: Grid voltages swell of 15%



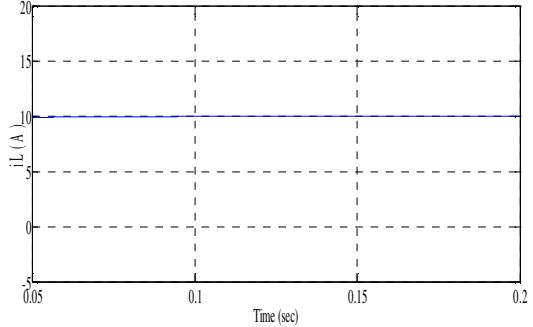
(a) Grid Voltage



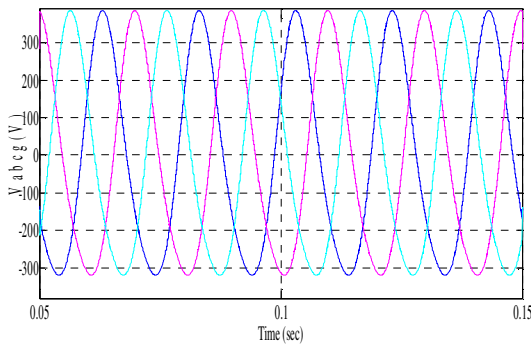
(b) The inverter output currents



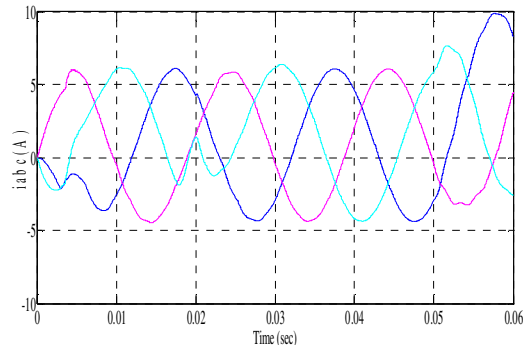
(c) The dc link voltage, V_{inv}



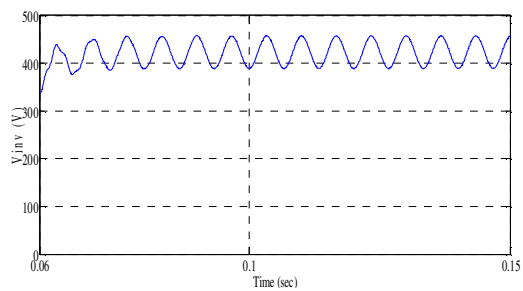
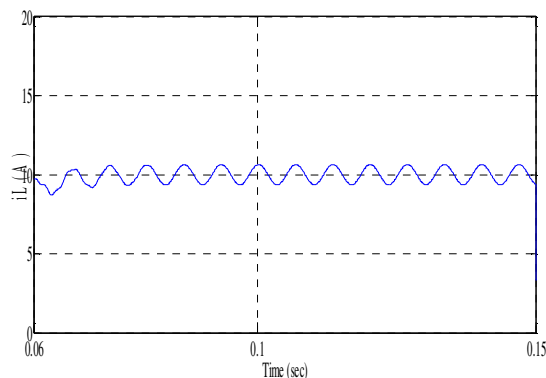
(d) Input current, i_L
Fig: Grid voltages sag of 15%



(a) Grid Voltage



(b) The inverter output currents

(c) The dc link voltage, V_{inv} (d) Input current, i_L

CONCLUSIONS

In this paper, 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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