Modelling and performance evaluation of PV controller in various reference frame

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ABSTRACT

Many closed-loop automations of grid-connected and standalone inverters use controllers for various process control. The performance of the voltage source inverter (VSI) used in such applications depends on the characteristics of the controller. The gating pulses for the inverter are generated based on controller output and it affects the overall performance of the system. In this regard, the design and performance analysis of the controllers becomes an important integral part of any system under consideration. There are various methods available to design a controller. This paper discusses the design, modeling, and performance of a PI controller for single-phase VSI in stationary and rotating reference frames which helps in selecting a controller for the specific system configuration. The dynamic behavior of the controller with respect to the above reference frames and its effects on VSI output when subjected to load disturbance is evaluated. The controller design is carried out with two different current control strategies namely inductor current and capacitor current sensing. The stability of the system with the designed controller is analyzed and the results are compared.

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1. INTRODUCTION

Controllers play a very important role in maintaining stability of voltage and current in a PV system. PI controllers are generally used in many applications that facilitate regulating voltage and current and hence control of power flow in a PV system. Control loops are nonlinear in nature and need a careful selection of control parameters. The main requirement of a power inverter is to produce and maintain a stable and sinusoidal output voltage waveform regardless of the type of load connected [1], [2]. Controllers can be implemented in different reference frames such as synchronous rotating (dq), stationary (abc) or (αβ) reference. Stationary frame PI regulators suffer from significant steady-state amplitude and phase errors. Synchronous frame dq frame regulator can achieve a zero steady-state error by acting on a dc signal in a rotating reference frame [3]-[5]. Coupling terms are associated with filter components. If coupling is ignored, it is found that unacceptable errors can occur and PI controller performance deteriorates [6]-[10]. Proportional integral (PI) based current controller has the great advantage of providing infinite gain at the steady-state operating point, which gives zero steady-state error. Frequency response methods lead to more powerful analysis and synthesis tools to assess stability and relative stability, as well as rejection of noise and disturbances. The absolute and relative stability of a closed loop system can be estimated from open loop frequency response [11]-[13].

A popular method for tuning PI controllers is the Ziegler–Nichol's method in which integral and differential gains are initialized to zero and then proportional gain is raised until the system is unstable. The value of K_P at the point of instability is called ultimate gain K_u; the frequency of oscillation is f_0 and the corresponding time period is ultimate time period T_u. In modulus, optimum method resulting system has a frequency of natural oscillation given by $\omega n = \frac{1}{Ta\sqrt{2}}$ and damping factor $\xi=\frac{1}{\sqrt{2}}$; where converter delay T_a is due to inverter switches. Calculating the inner current loop time constant T_c and outer voltage loop time constant T_v, the system can be tuned for a desired value of crossover frequency. Tuning methods are based on either frequency characteristics or on time domain. Any improper design produces overshoots and oscillatory responses which are not acceptable practically [14]-[16]. For applying dq concepts in a single phase, the system should have a real component and a fictitious component with identical characteristics with 90^0 phase shift with respect to the real component. The concept is realized by generating a second signal with a time delay of ¼ th cycle of the actual time period of the real signal. Orthogonal quantities can create a rotating frame [17]-[19].

The filter inductor is usually sized to limit high-frequency ripple current and the corner frequency of LC filter is typically chosen below the switching frequency of the inverter to obtain less total harmonic distortion (THD). LC filter is most efficient in suppressing the current harmonics occurring from the switching frequency and also in minimizing power loss [20], [21]. The bandwidth of linear controllers is dependent on the switching frequency. Time delays due to modulation and digital computations limit controller bandwidth and affect its stability margins [22], [23]. The PWM inverter results in a lesser peak ripple current. At high switching frequencies output current harmonics reduce. High current ripple results in high losses and unacceptable current stresses across the switching devices [24], [25]. This paper investigates and evaluates the performance of a single-phase voltage source inverter (VSI) with an LC filter using sinusoidal pulse width modulation or SPWM switching with respect to various control strategies with PI controller for cases as shown in Figure 1. The performance of the designed and developed controllers is compared for dynamic resistive and inductive loads.

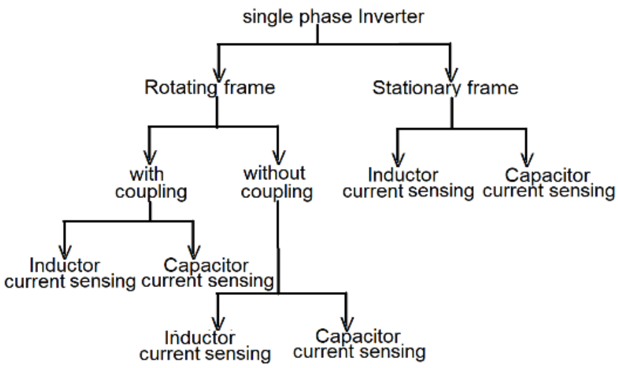


Figure 1. Various control strategies

2. SYSTEM SPECIFICATIONS AND DESIGN

The typical PV system consists of a PV panel, DC-DC Converter, and inverter connected to a load. To obtain the desired output with variation in load, it is necessary to design and implement a closed-loop controller for the PV system. The closed loop single phase VSI has an inner current loop and an outer voltage loop as shown in Figures 2(a) and 2(b). The performance of the outer voltage loop depends on the inner current loop.

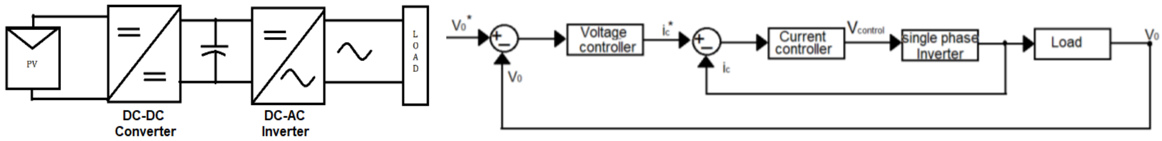


Figure 2. Block diagram: (a) PV system and (b) inverter closed loop

The inverter specification, PI controller parameters designed, and various transformation equations used are shown in Tables 1-3. Using the transformation matrix Simulink model developed for dq transformation is shown in Figure 3. Figure 4(a) and (b) shows a single-phase inverter circuit with LC filter connected to the load.

Table 1. Inverter and load specifications

Parameter	Specifications	Parameter	Specifications
Input DC	432 V	Load2	50 Ω,10 mH
Output AC	220 Vrms	Filter L_f	15 mH
Switching frequency	1 KHz	Filter capacitance C_f	10 µF
load 1	10 Ω		

Table 2. Tuning rules

Tuning method	Design equations	K_p	K_i	Voltage controller K_{pV}	Voltage controller K_{iV}	Current controller K_{pC}	Current controller K_{iC}
Ziegler Nicholas	K_u T_u	$0.45K_u$	$\frac{T_u}{1.2}$	0.45	100	0.19	1
Modulus Optimum	$T_a = \frac{1}{2f_{sw}}$ $T_c = 2T_a$ $T_v = 4T_a$	$\frac{C}{T_V}$ $\frac{L}{T_c}$	$\frac{R_c}{T_v}$ $\frac{R_L}{T_c}$	10	100	3.9	1

Table 3. Transformation matrix

Transformation	Conversion	Matrix
Park	αβ to dq	$\begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix}$
Inverse Park	dq to αβ	$\begin{pmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{pmatrix}$

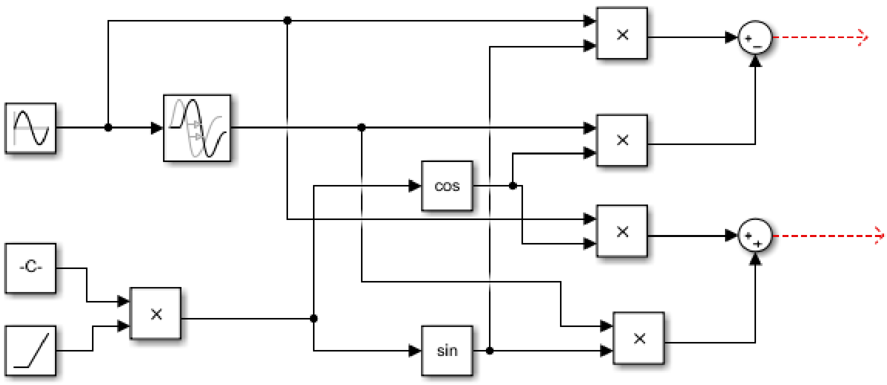
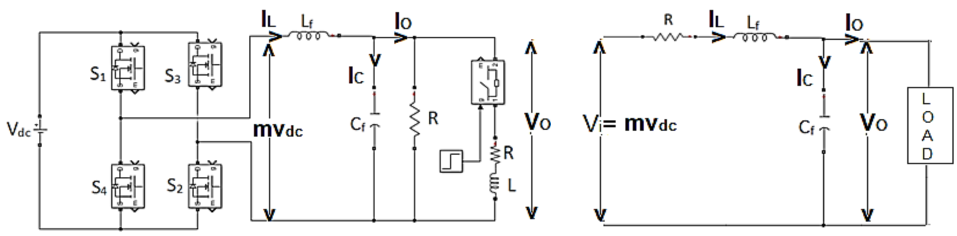


Figure 3. Single-phase Simulink model of DQ transformation



(a) (b)

Figure 4. Single phase inverter: (a) basic circuit and (b) equivalent model

2.1. Model equations with filter inductance

The mathematical model of the system is derived from an equivalent circuit. Applying Kirchhoff's voltage law to the loop containing V_i – R - L_f - load in the circuit as shown in Figure 4; (1)-(3) are obtained. Filter inductance with d and q coupling components is considered while writing equations.

$$V_i = L_f \frac{d_i}{d_t} + Ri + V_0 \quad (1)$$

$$V_{id} = L_f \frac{d_i}{d_t} + Ri + V_0 - \omega L_f i_q \quad (2)$$

$$V_{iq} = L_f \frac{d_i}{d_t} + Ri + V_0 + \omega L_f i_d \quad (3)$$

Where, $i = I_L$, V_{id} and V_{iq} are d and q components of voltage V_i

2.2. Model equations with filter capacitance

Applying Kirchhoff's current law at the node where L_f - C_f - load is meeting at a point in the equivalent circuit as shown in Figure 4; mathematical models (4)-(7) are obtained. Filter capacitance with d and q coupling components is considered while writing equations.

$$i_L = i_C + i_0 \quad (4)$$

$$i_L = C \frac{dv}{dt} + i_0 \quad (5)$$

$$i_{cd} = i_L - i_0 + \omega C_f v_{cq} \quad (6)$$

$$i_{cq} = i_L - i_0 - \omega C_f v_{cd} \quad (7)$$

Where, i_{cd} and i_{cq} are d and q component of the current i_C. $\omega L_f i_d$ and $\omega L_f i_q$ are called cross-coupling components with respect to filter inductance. Similarly with respect to filter capacitor $\omega C_f v_{cd}$ and $\omega C_f v_{cq}$ are cross-coupling components.

3. MODELLING OF SINGLE-PHASE VSI

Determination of a mathematical model of a physical system is important in design and analysis. The model relates various variables of the system in a quantitative manner. The mathematical model of the single-phase inverter is shown in Figure 5. The transfer function and Simulink model developed for VSI and Controller performance with stationary frame design are shown in Figure 6(a) and 6(b) and also Figure 7. The values for K_p and K_i of controllers and other parameters are chosen as per Tables 1-2. From the results obtained, it is observed that when the load changes at t=1sec voltage disturbance that occurred is corrected within 0.4sec making VSI operate at a steady state.

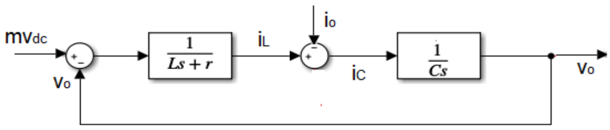


Figure 5. Mathematical model of single-phase inverter

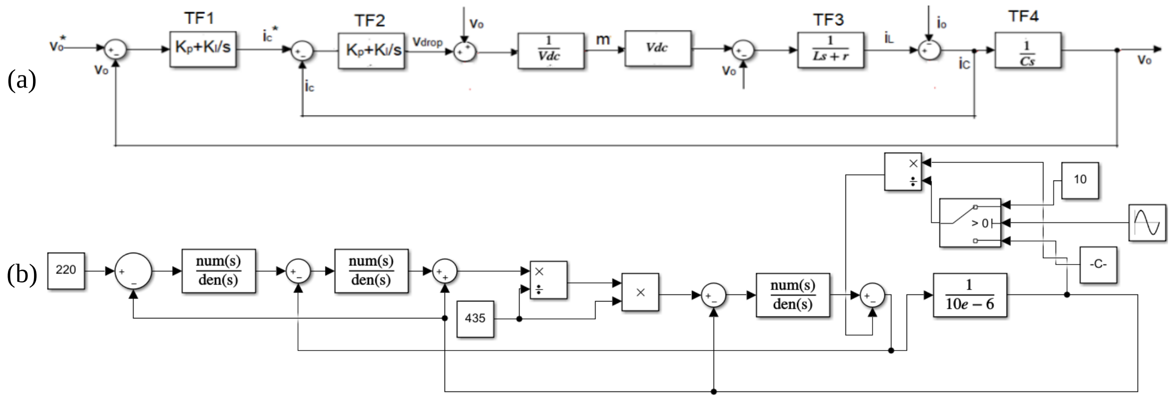


Figure 6. VSI control with stationary frame: (a) transfer function model and (b) simulation model

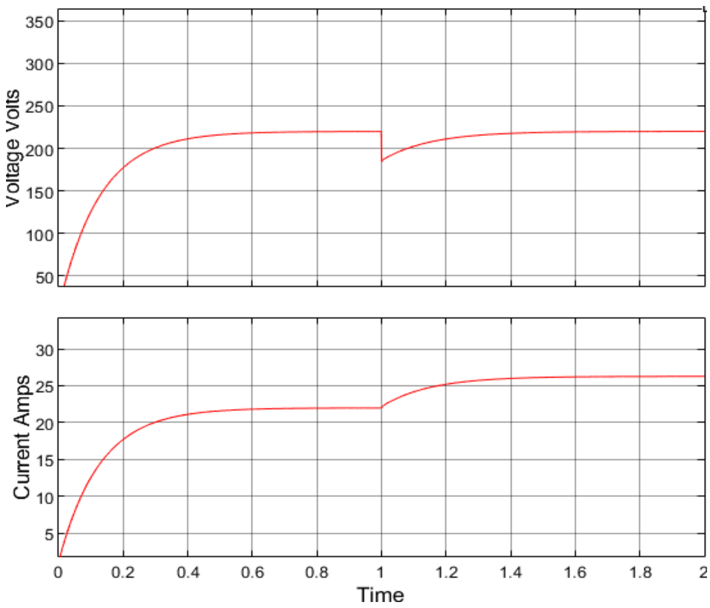


Figure 7. VSI output voltage and current waveforms with stationary frame

The transfer function and Simulink model developed for VSI and controller performance with rotating frame design are shown in Figure 8(a) and (b) (see Appendix) and also Figure 9. From the results, it is observed that when load changes at t=1sec voltage disturbance occurred is corrected faster within 0.35sec compared to stationary frame design making the inverter operate at a steady state.

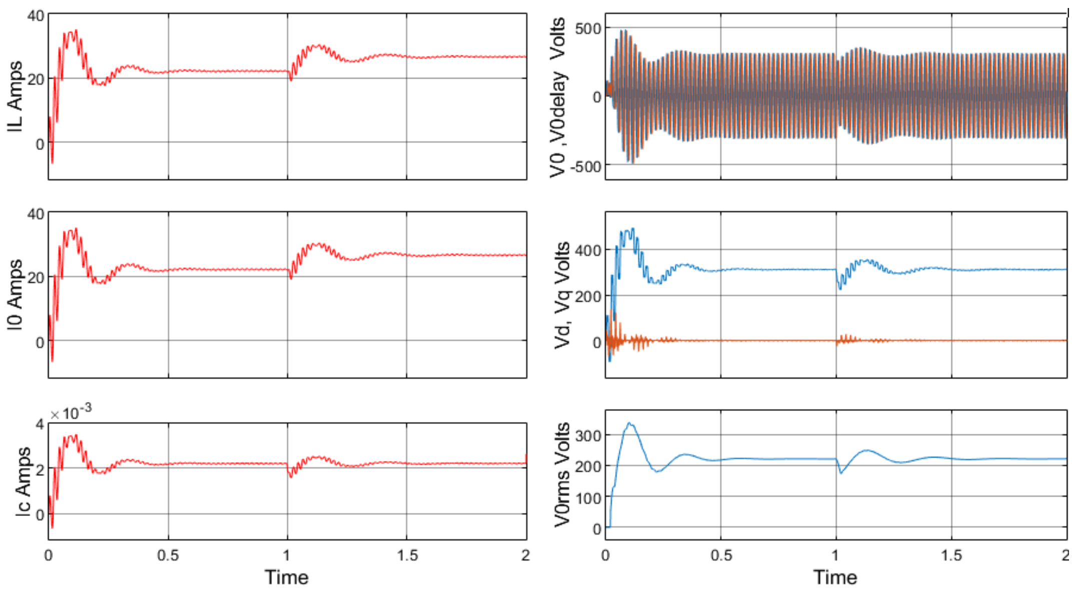
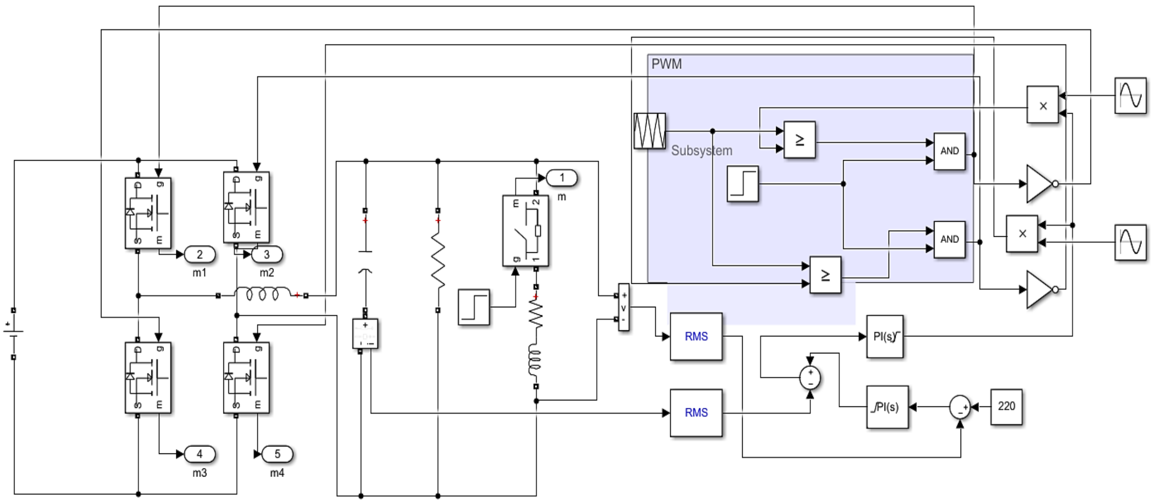


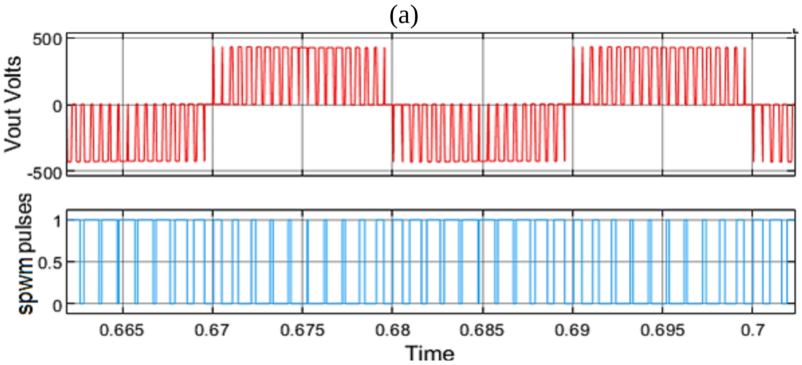
Figure 9. Current and voltage waveforms of VSI with rotating reference

4. PERFORMANCE OF SINGLE-PHASE VSI WITH VARIOUS CONFIGURATION

The controller requirements are different in standalone and grid-tied modes of operation. By controlling the amplitude and phase of the command signal to the SPWM generator, the output voltage is controlled. Either capacitor current or inductor current as feedback can be used to control the duty cycle of the VSI. Simulink models developed using MOSFET as a switching device and SPWM pulses generated for stationery and reference frame design is shown in Figure 10(a) and 10(b) and also Figure 11 (see Appendix). Figures 12-17 show inverter outputs and controller performance in stationary and rotating reference frame designs. Results observed from simulations are tabulated in Table 4.



(a)



(b)

Figure 10. VSI with stationary frame (a) Simulink model and (b) output voltage and SPWM pulses generated

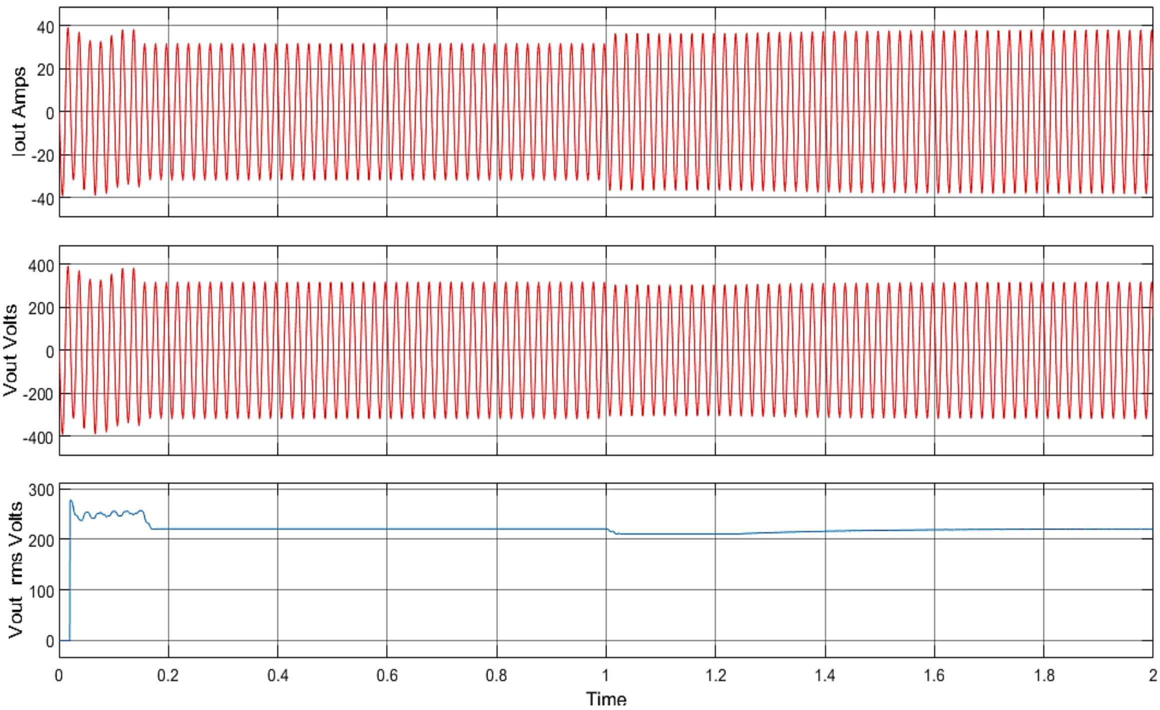


Figure 12. Stationary frame output voltage with inductor current sensing

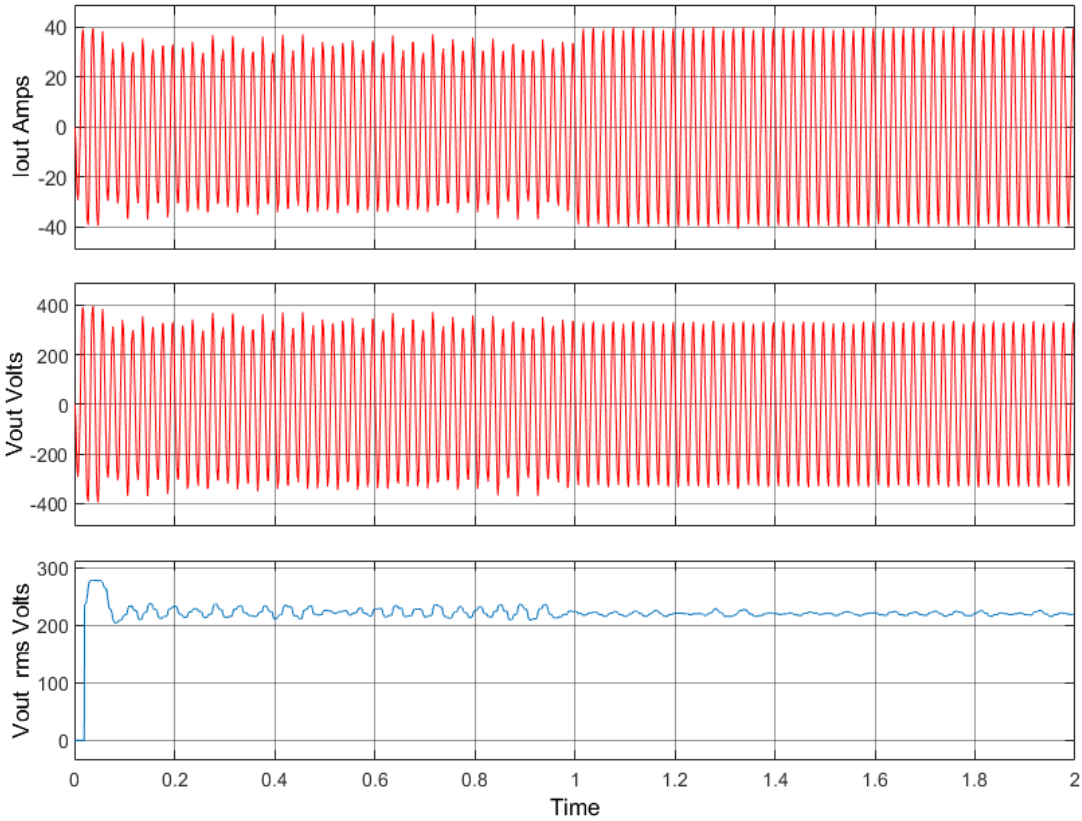


Figure 13. Stationary frame output voltage with capacitor current sensing

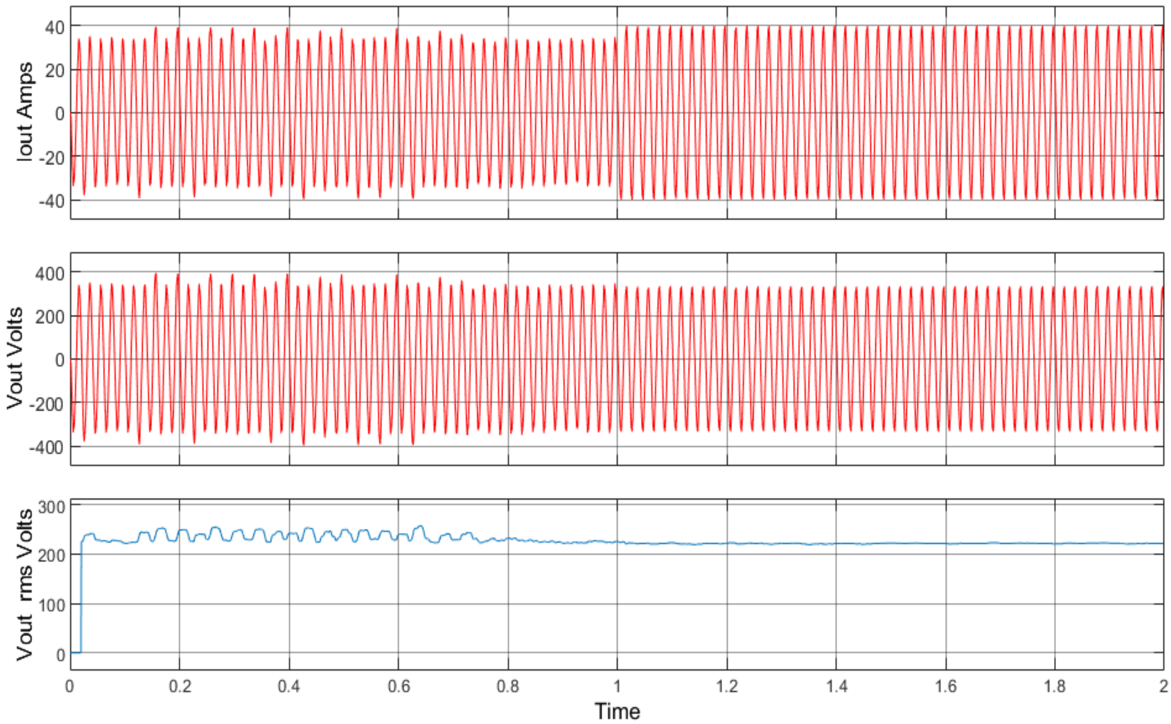


Figure 14. Rotating frame output voltage with inductor current sensing without coupling

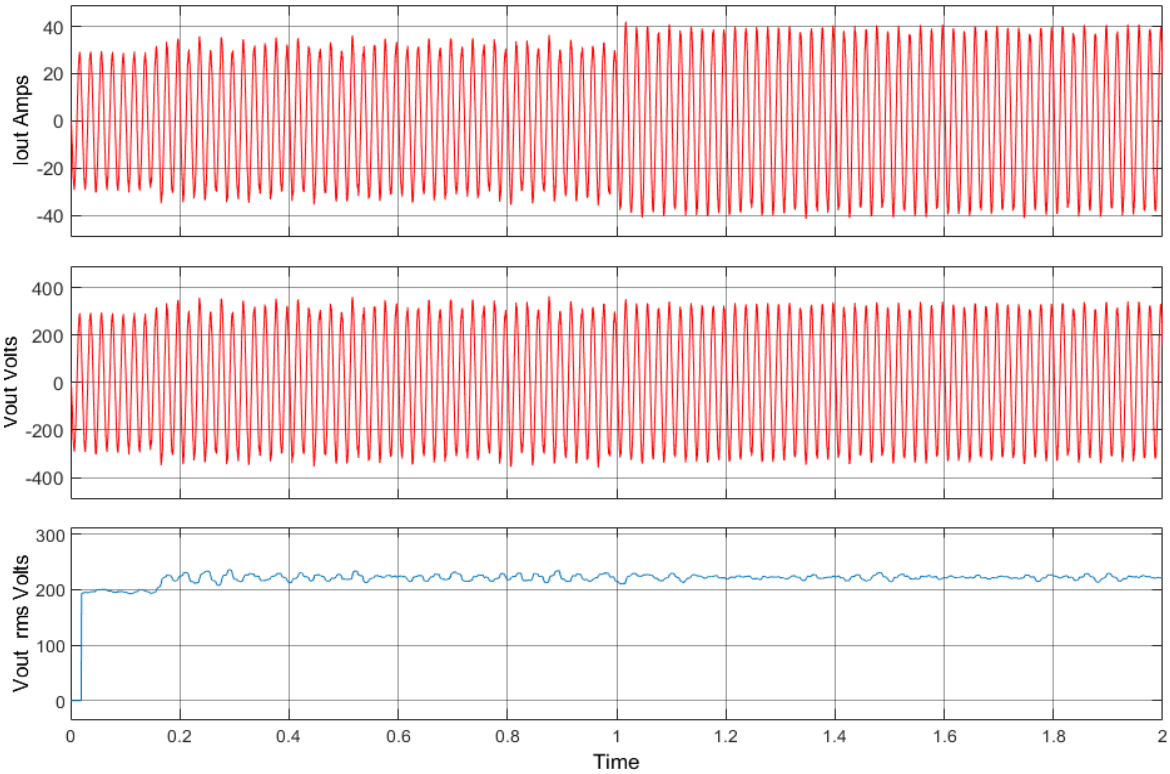


Figure 15. Rotating frame output voltage with capacitor current sensing without coupling

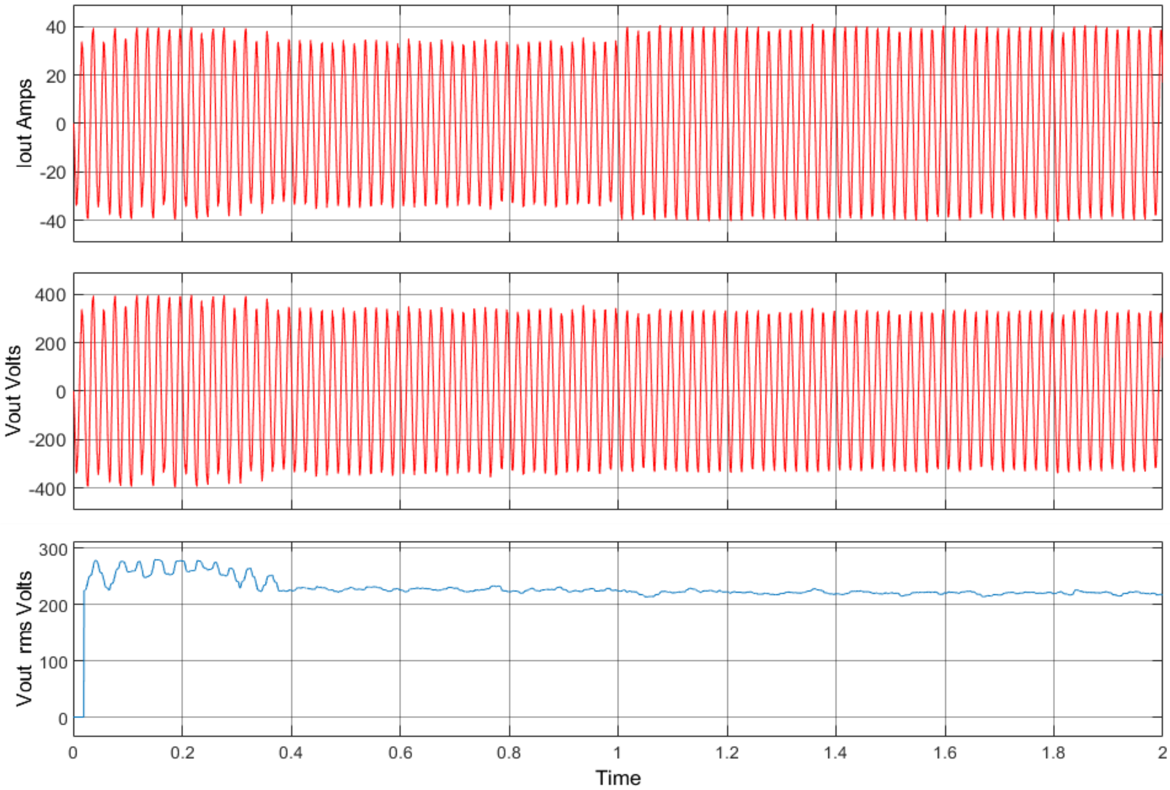


Figure 16. Rotating frame output voltage with inductor current sensing with coupling

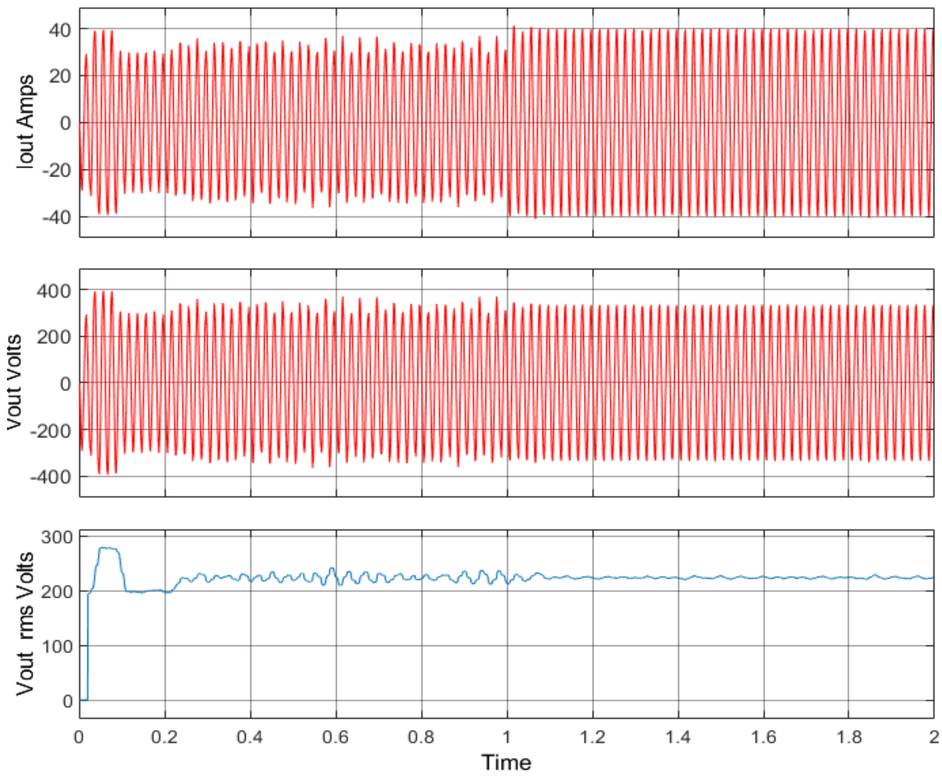


Figure 17. Rotating frame output voltage with capacitor current sensing with coupling

Table 4. Comparison between various controllers

Feedback type & frame	Duty ratio	V_{01} Volts	% THD	K_{pv}	K_{iv}	K_{pc}	K_{ic}	% Over shoot	Settling time ms
Stationary: inductor current	0.834	312.2	5.67	0.45	100	0.19	1	26	165.35
dq : inductor current without coupling	0.81	322.5	7.19	0.45	10	0.3	100	9.81	916.667
dq : inductor current with coupling	0.81	325.1	8.06	0.45	10	0.3	100	26.59	398.294
Stationary: capacitor current	0.8041	314.4	6.71	0.3	100	0.15	100	26.82	70.21
dq : capacitor current without coupling	0.8249	310.9	5.75	0.3	10	0.3	100	0%	168.63
dq : capacitor current with coupling	0.8098	315.7	7.02	0.3	10	0.3	100	26.9	229

5. STABILITY ANALYSIS OF THE CURRENT AND VOLTAGE CONTROLLER

The closed loop control model of single-phase VSI with transfer functions for stability analysis is shown in Figure 18. The current and voltage controller transfer function for the designed values obtained is shown in (8)-(9). From Bode plot as shown in Figure 19, it is observed that designed controller is in stable mode.

$$G_c(s) = \frac{i_c}{i_c^*} = \frac{0.15}{1+0.0005S} \quad (8)$$

$$G_v(s) = \frac{v_0}{v_0^*} = \frac{0.3\left(s+\frac{100}{0.3}\right)}{s} * \frac{0.15}{(1+0.0005s)} * \frac{1}{10e-6s} \quad (9)$$

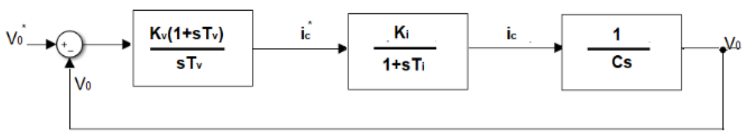


Figure 18. Transfer function of VSI with current and voltage controller

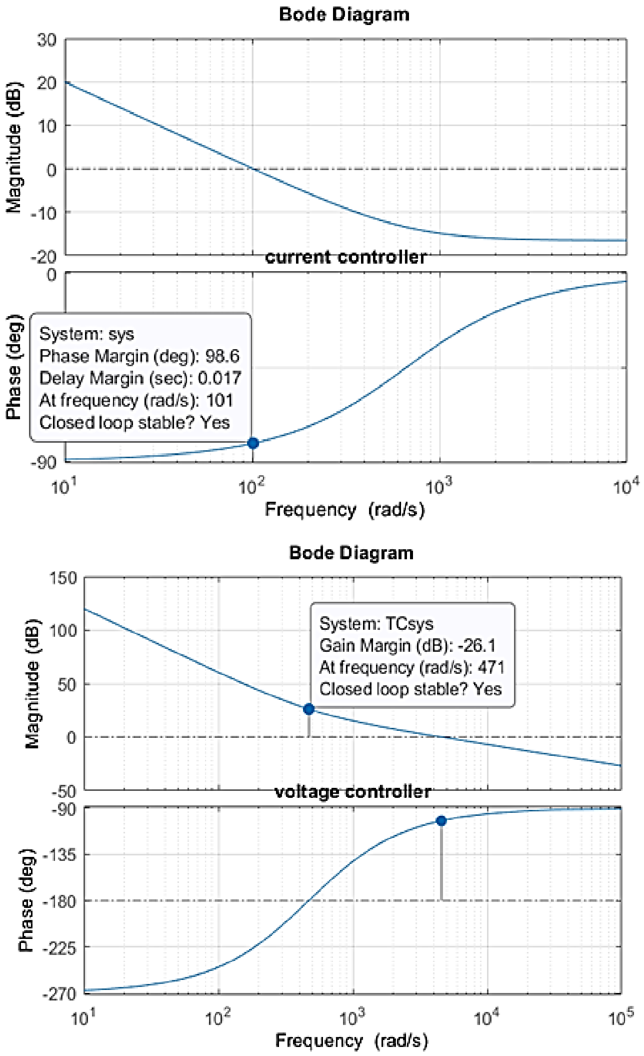


Figure 19. Bode plot of the current and voltage controller

6. RESULTS AND DISCUSSION

The simulated results of controller performance for different cases is shown in Table 4. In addition, transient, and steady-state response as well as total harmonic distortion (THD) is tabulated. From simulation results it is observed that compared to inductor current sensing, capacitor current as feedback acts faster in correcting the error with lesser THD.

7. CONCLUSION

In this paper, modelling and design of controller in stationary and rotating reference frame for single-phase VSI is discussed. Performance of VSI with inductor current and capacitor current as feedback with dynamic resistive and inductive load is evaluated. The stability analysis of the system with the designed controller is performed and is observed that system is stable. It is also found that controller performance for stationary frame is better compared to rotating (dq) frame inductor current and capacitor current sensing method. However, for applications where independent control of real and reactive component of current needs to be controlled, dq capacitor feedback method performance is found to be better from the results observed.

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APPENDIX

(a)

(b)

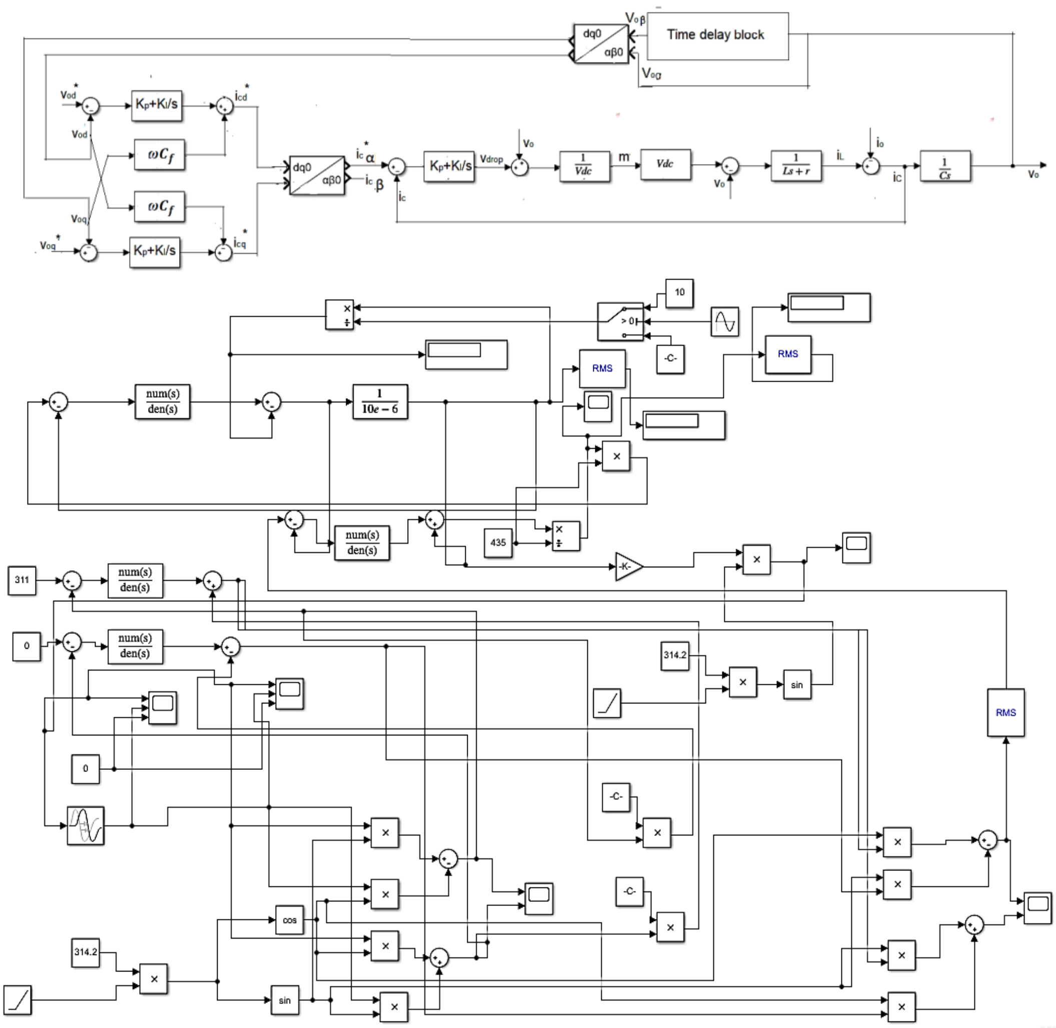

Figure 8. VSI control with rotating frame (a) transfer function model and (b) simulation model

(a)

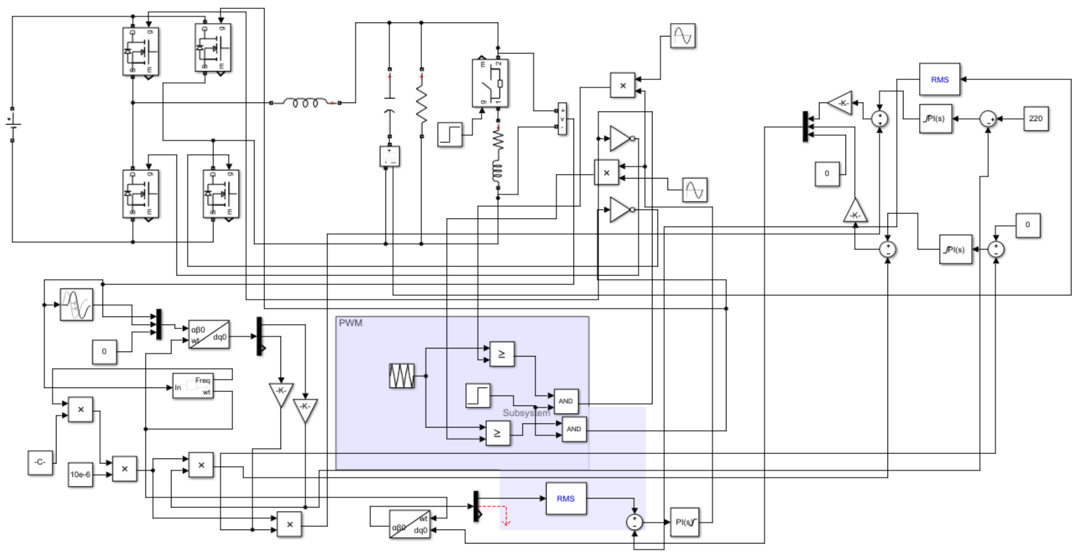

Figure 11. VSI with rotating frame: (a) Simulink model

(b)

(c)

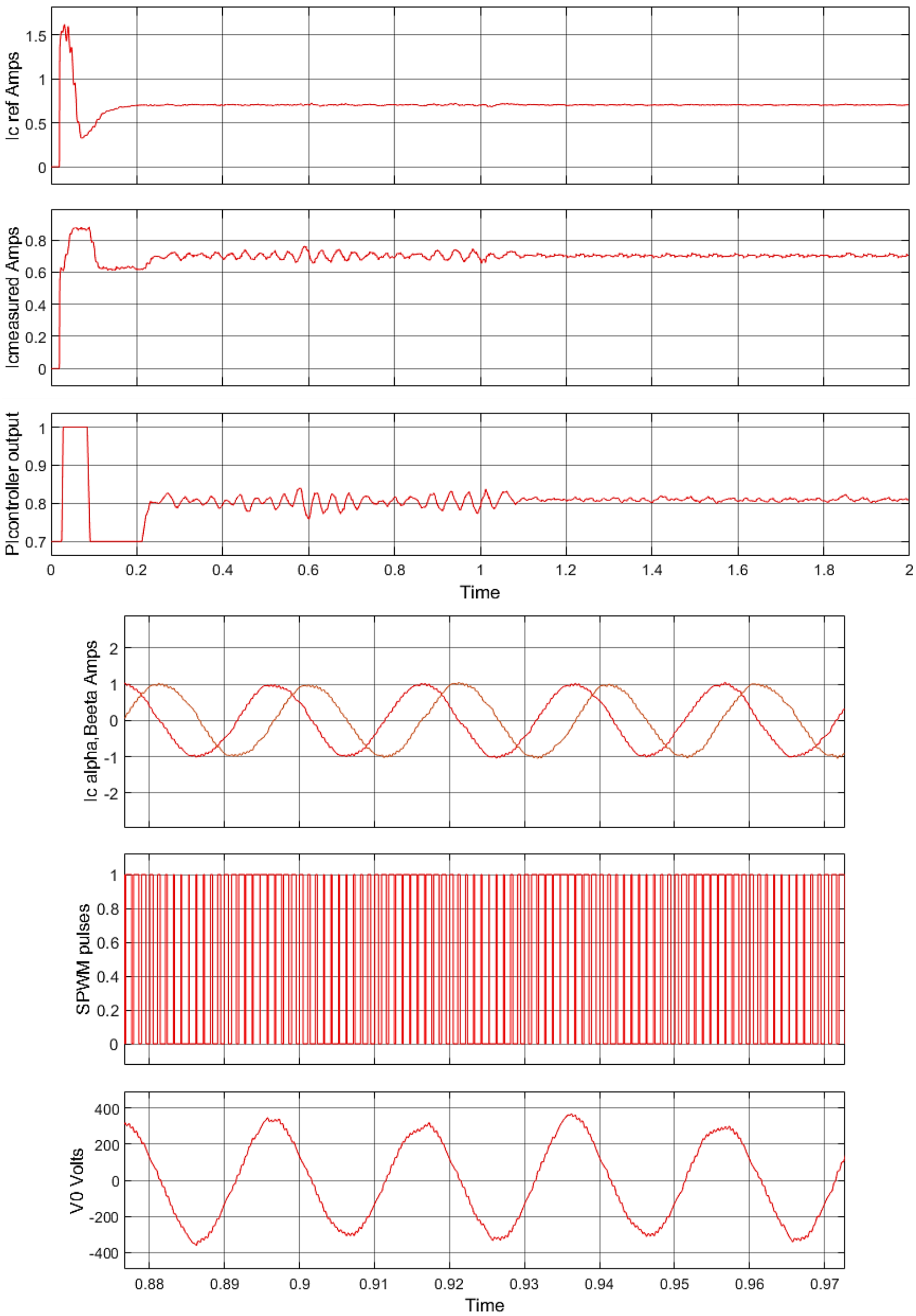

Figure 11. VSI with rotating frame: (b) controller output and (c) SPWM pulses (continued)

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