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Performance analysis of current control technique with RSVPWM and discrete model predictive control technique for 3-Phase voltage source inverters

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Voltage Source Inverter (VSI) is one of the essential Power Electronic Converters (PEC) which is used to utilize the power from the Renewable Energy Sources (RES) in an efficient manner. Some of the RES produces power in the form of the dc. VSI is used to convert the dc power into ac power. Various control techniques are implemented to control the inverter circuits. This paper presents a performance analysis of current control with Revised Space Vector Pulse Width Modulation (RSVPWM) technique and Discrete Model Predictive Control (DMPC) technique. This analysis is performed on 3-phase VSI. Basic concepts, control circuits, mathematical models are explained and the control techniques are simulated using MATLAB / Simulink tool. Simulation results are presented and performances of the both control techniques are compared.

***Keywords*:** *Power electronic converters, Renewable energy sources, Voltage source inverters*

1.0 INTRODUCTION

Renewable Energy Sources (RES) like wind, solar and bio-mass are being used to meet the increasing power demand around the world. It is found that some of the RES produces dc power and VSI is used to efficiently utilize the power by converting dc into ac power. Novel control techniques are essential to control the 3-phase VSI [1]. The controllers are basically classified as linear and non-linear type. Linear controller is a voltage and current controller with proper Pulse Width Modulation (PWM) schemes. Non-linear controllers are fuzzy logic controller, hysteresis controller, adaptive controller etc. Current developments in the field of Digital Signal Processors (DSP) lead to utilization of more complex control techniques for 3-phase VSI. Traditionally control requirements were mainly associated with dynamic performance and stability of the system.

Control strategies for power converters have been the subject of research in the area of power electronics. Currently, industry requires more demanding technical specifications and constraints, and in many cases it is subjectedto regulations and codes. Now a days hardware and software solutions are implemented in Digital Signal Processors (DSP) and Field Programmable Gate Array (FPGA) are used. Many of these requirements enforce operating limits and conditions that cannot be only dealt by the hardware but also need to be addressed by the control system. This brought the idea to developthe new control techniques. Power converters are switched system that inherently generates harmonic content. This harmonic content is measured in terms of Total Harmonic

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Distortion (THD). Many systems have limitations and restrictions on harmonic introduced by the modulation stage.

The Electromagnetic Compatibility (EMC) and Electromagnetic Inference (EMI) of the system must be considered according to standards and regulations. Power converters have basically nonlinear characteristics; it is tough to achieve better voltage regulation when the controller has been adjusted for a single operating point of the linearized system model.

Some of the power converter networks have their own restrictions and constraints such as forbidden switching states, power unbalances, mitigation of resonances and many other specific requirements.

Power converters are non-linear systems of a hybrid nature and the input signals for power electronic devices are discrete signals that command the turn-on and turn-off transitions of each device. Several constrain and restrictions need to be considered by control system, some of which are inherent to the system like maximum output voltage of the inverter, while others are imposed for security reasons, like current limitations to protect the converter and its loads. All control techniques are implemented using digital control platform. So designing any control system must take into account the model of the plant for adjusting the control parameters which in the case of power converters is well known. All these characteristics of the power converters as well as characteristics of the control platforms used to form the control, converge in a natural way to the application of model predictive control [2]. This paper presents a performance analysis of current control with Revised Space Vector Pulse Width Modulation (RSVPWM) technique and Discrete Model Predictive Control (DMPC). Both techniques are mathematically modelled and simulated using MATLAB/Simulink tool. This paper has been organized as follows. In section 2, modelling of current controller with RSVPWM has been explained and in section 3, DMPC have been explained. Simulation results are given in section 4 and last section has conclusions.

2.0 MODELLING OF 3-PHASE VSI WITH CURRENT CONTROLLER AND RSVPWM

Functional block diagram of the 3-phase VSI with current control technique and RSVPWM is shown in Figure 1. This circuit contains 3-phase VSI in which IGBTs are used as switching devices (S1-S6). When x=1, upper switch S1 is ON and the corresponding lower switch S4 is OFF. LC circuit is used as filter to remove the harmonics produced by the inverter [3]. Load part is considered as a RL circuit. Inverter circuit has been modeled using state space analysis. From the block disgram shown in Figure 1, apply KCL and KVL at the point X,Y,Z, the equations are expressed as

$$\frac{dV_{Load}}{dt} = \frac{I_{iphase}}{3C} - \frac{Z * I_{Load}}{3C} \quad ....(1)$$

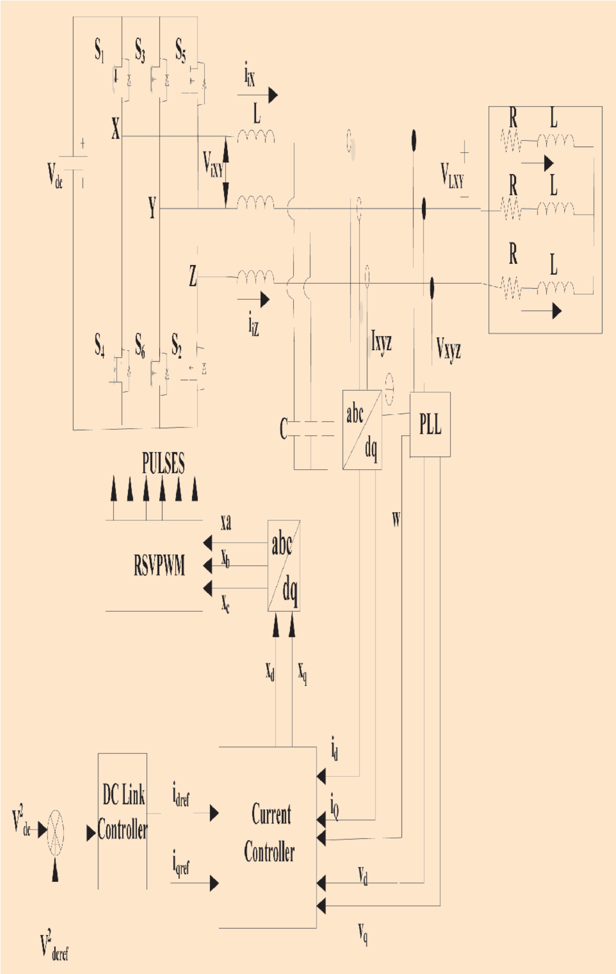

FIG. 1 BASIC STRUCTURE OF THE CURRENT CONTROLLER

$$\frac{dI_{iphase}}{dt} = \frac{-V_{Load}}{L} + \frac{V_{iphase}}{L}$$

$$Z = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 1 & 0 & 1 \end{bmatrix} I_{iphase} = \begin{bmatrix} i_{iX} - i_{iY} \\ i_{iY} - i_{iZ} \\ i_{iZ} - i_{iX} \end{bmatrix}$$

$$V_{Load} = \begin{bmatrix} V_{LXY} \\ V_{LYZ} \\ V_{LZX} \end{bmatrix}, I_{Load} = \begin{bmatrix} i_{LX} \\ i_{LY} \\ i_{LZ} \end{bmatrix}, V_{iphase} = \begin{bmatrix} V_{iXY} \\ V_{iYZ} \\ V_{iZX} \end{bmatrix} \quad ....(2)$$

Using transformation theory, abc system is converted into dq coordinate system, then

$$\frac{dV_{Loaddq}}{dt} = \frac{I_{iphasedq}}{3C} - \frac{Z_{phase} * I_{Loaddq}}{3C} \quad ....(3)$$

$$\frac{dI_{phasedq}}{dt} = \frac{-V_{Loaddq}}{L} + \frac{V_{iphasedq}}{L} \quad ....(4)$$

Finally the entire VSI system model is expressed using continuous-time state space equation

$$X(\dot{t}) = Ax(t) + Bu(t) \dot{+} Ed(t)$$

$$X = \begin{bmatrix} V_{Ldq} \\ I_{idq} \end{bmatrix} A = \begin{bmatrix} 0_{2X2} & \frac{1}{3C} I_{2X2} \\ \frac{-1}{L} I_{2X2} & 0_{2X2} \end{bmatrix}_{4X4}$$

$$B = \begin{bmatrix} \frac{-1}{3} Z_{base} \\ 0_{2X2} \end{bmatrix}_{4X2} \quad u = \begin{bmatrix} V_{id} \\ V_{iq} \end{bmatrix} B = \begin{bmatrix} 0_{2X2} \\ \frac{-1}{L} I_{2x2} \end{bmatrix}_{4X2} \quad d = \begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} \quad ....(5)$$

2.1 Current Controller with RSVPWM

Conventional current controller is shown in Figure 2. This controller is combined with the dc link voltage controller and current controller [4]. The reference voltage components produced from the controller is given in (6) and (7).The PWM switching signals for VSI is generated by transforming the d-q components to abc components and these signals are given to Revised Sinusoidal Pulse Width Modulation (RSPWM) block which is generating required pulse pattern for the inverter circuit.

$$x_d = v_d - k_p \varepsilon_d - k_i i_d + \omega L i_q \quad ....(6)$$

$$\mathrm{x_q = v_q - k_p \varepsilon_q - k_i i_q - \omega L} i_d \quad ....(7)$$

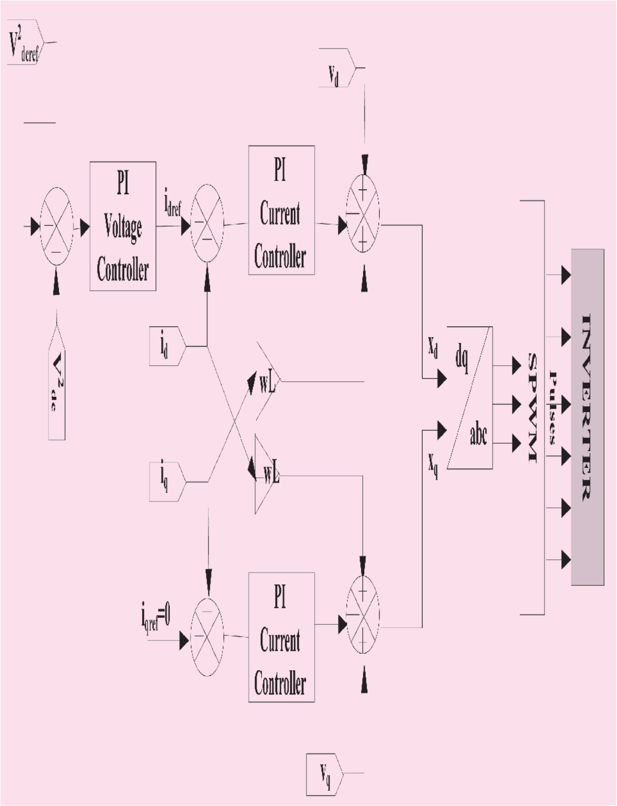

FIG. 2 CONVENTIONAL CURRENT CONTROLLER

2.2 Conventional SVPWM

SVPWM is employed to generate the desired output voltage vector V in d-q reference frame and it is shown in Figure 3. For a three phase VSI there are totally eight possible switching patterns and each of them determines a voltage space vector. As shown in Figure 4, eight voltage space vectors divide the entire vector space into six sectors namely 1-6. Except two zero vectors Vo and V7, all other active space vectors have same magnitude of (2/3) V_{dc}. In SVPWM, the reference voltage vector should be synthesized by the adjacent vectors of the located sector in order to minimize the switching times and to minimize the current harmonics. The eight vectors, called the basic space vectors include two zero vectors V0 and V7 and six non-zero V1-V6 vectors. Two zero vectors have zero magnitude and six non-zero vectors have the same amplitude as shown in Figure 4. The angle between any adjacent two non-zero vectors is 60 degrees [5].

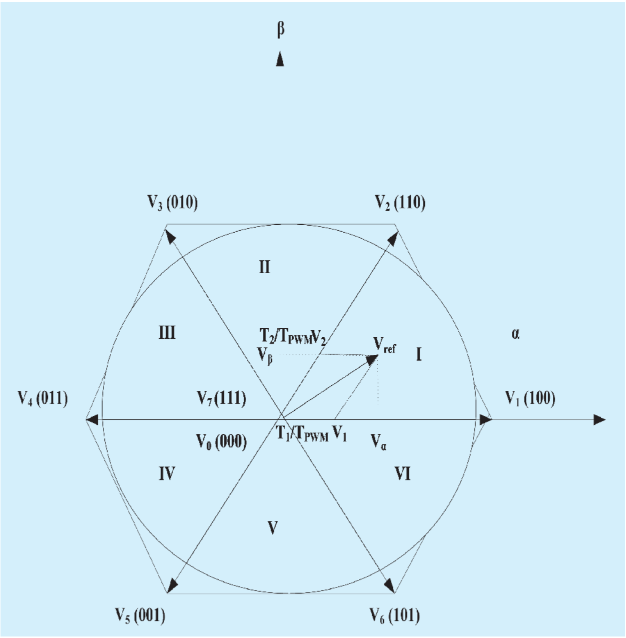

FIG. 3 SVPWM

2.3 RSVPWM

In the conventional SVPWM, the reference voltage vector is synthesized by the adjacent vectors of the located sector in order to minimize the switching times and to minimize the current harmonics. To make the reference voltage, three switching durations are found by using nearby voltage vectors and the time durations are expressed as

$$T_1 = T_z \frac{V_{ref}}{\frac{2}{3}V_{dc}} \frac{\sin\left(\frac{\pi}{3} - \alpha\right)}{\sin\left(\frac{\pi}{3}\right)}, T_2 = T_z \frac{V_{ref}}{\frac{2}{3}V_{dc}} \frac{\sin(\alpha)}{\sin\left(\frac{\pi}{3}\right)} T_0 = T_z - (T_1 + T_2) \quad \text{....(8)}$$

So to utilize the dc link voltage effectively, consider the time duration (T_{sh}) of shoot through zero vectors. From the basic SVPWM technique, a new time period $T=T_{sh}/3$ is added or subtracted as shown in Figure 5 and RSVPWM is obtained. Each phase leg still switches on and off once per switching cycle (T_z). Each phase has only one shoot-through zero state (T) during one period (T_z) in any sector without the change of total zero vectors (V_0, V_7, and T) and total nonzero switching vectors (V_1– V_6). Even if the output voltage of inverter and DC-link voltage can be controlled by adjusting T_{sh}, the maximum available shoot-through interval (T_{sh}) to boost the DC-link voltage (V_{dc}) is restricted by the zero vector duration ($T_0/2$) which is determined by the modulation index.

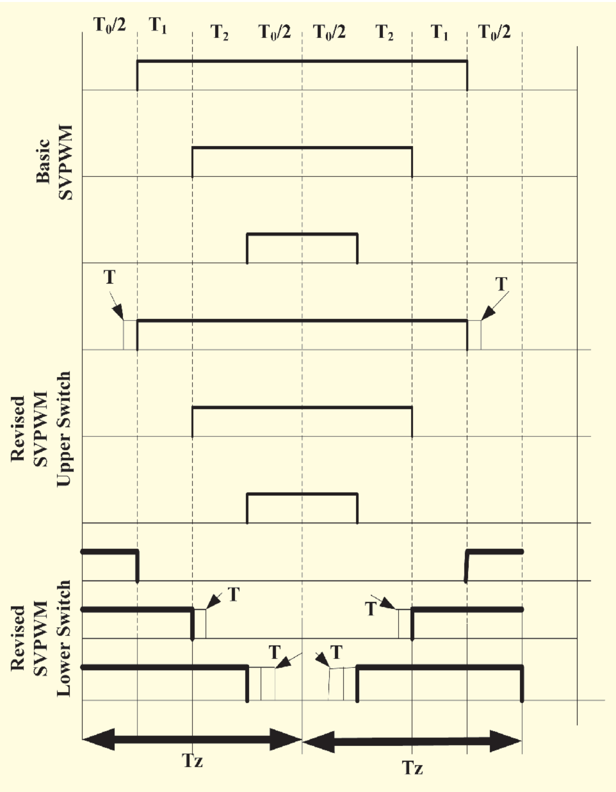

FIG. 4 INVERTER SWITCHING STATE

3.0 DISCRETE MODEL PREDECTIVE CONTROL

The DMPC technique is based on the fact that only a finite number of possible switching states can be generated by a static power converter and the models of the system can be used to predict the behaviour of the variables for each switching state. For the selection of the appropriate switching state to be applied, a selection condition should be defined. This condition consists of a cost function that will be evaluated for the predicted values of the variables to be controlled. Prediction of the future value of these variables is calculated for each possible switching state and then the state that minimizes the cost function is selected. First cost function is defined and converter model and possible switching states should be defined and finally load model or grid model should be defined [6]. Basic structure of DPMC scheme is shown in Figure 5.

The main objective of current control scheme is to minimize error between the measured currents and reference values. This requirement can be written in the form of a cost function. The cost function is [4] expressed in orthogonal coordinates and measures the error between references and predicted values.

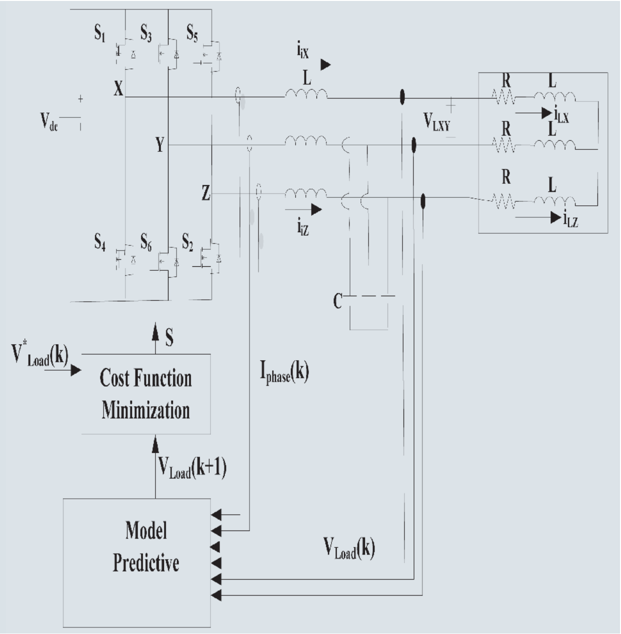

FIG. 5 DISCRETE MODEL PREDECTIVE CONTROL

The cost function is expressed as

$$g = (V_{Loadr}^{*} - V_{Loadr})^2 + (V_{Loadimg}^{*} - V_{Loadimg})^2 \quad \text{....(9)}$$

Here V^*_{Loadr} and $V^*_{Loadimg}$ are the real and imaginary part of the load voltage reference and V_{Loadr} and $V_{Loadimg}$ are the predicted load voltage $V_L(k+1)$, where k is the switching state for the next state. The cost function is used to reduce the voltage error.

3.1 Converter Model

For a given 3-phase VSI, the switching signal S is expressed as

$$S = \frac{2}{3}(S_X + aS_Y + a^2 S_z) \quad where\vec{a} = e^{j2\pi/3} \quad \text{....(10)}$$

And output voltage vector expressed in terms of inverter phase voltages

$$V = \frac{2}{3}\left(V_{xN} + aV_{yN} + a^2 V_{zN}\right) \quad \text{....(11)}$$

Switching signals S_x, S_y, S_z produce eight voltage vectors. But V_0=V_7, so only seven voltage vectors are considered [6-8].

LC filter and load circuit have been modeled and described by mathematical equations and finally continuous time state space equation is expressed as follows:

$$X(t) = A\dot{X}(t) + Bu(t)$$

$$X = \begin{bmatrix} V_{Load} \\ I_{iphase} \\ I_{Load} \end{bmatrix}_{9x1}$$

$$A = \begin{bmatrix} 0 & \frac{1}{3C} I_{3X3} & \frac{-1}{3C} I_{3X3} \\ \frac{-1}{L} I_{3X3} & 0 & 0 \\ \frac{1}{L_{load}} I_{3x3} & 0 & \frac{-R_{load}}{L_{load}} I_{3X3} \end{bmatrix}_{9X9} \quad B = \begin{bmatrix} 0 \\ \frac{1}{L} I_{3X3} \\ 0 \end{bmatrix}_{9X3} \quad u = [V_i]_{3x1} \quad \text{....(12)}$$

Here variables I_{iphas} and V_{load} are measured and I_{load} is considered as an unknown variable. For the given sampling time T_s, discrete time model of the system is expressed as

$$X(k+1) = AX(k) + BV_i(k) \quad \text{....(13)}$$

So to predict the load voltage the value of load current is needed. Basically the load current is obtained by

$$I_{Load}(k-1) = I_{iphase}(k-1) - \frac{C}{T_s}\left(V_{load}(k) - V_{load}(k-1)\right) \quad \text{....(14)}$$

The value of the load voltage$V_L(k+1)$ at the next sampling instant is calculated by using (12) and seven predictions are obtained for $V_L(k+1)$ and finally compared with a cost function g.

4.0 SIMLATION RESULTS AND DISCUSSION

Simulation of the system shown in Figure 1 and Figure 5 has been carried out using MATLAB / Simulink tools. System parameters are considered as, $R_{load} = 5\Omega$, $L_{load} = 2Mh$, $F = 50Hz$, $Ts = 1/F$, $V_{dc} = 400V$, $L = 800\mu H$, $C = 400\mu F$. Simulation results for both techniques are given in Figure 6 and Figure 7. DMPC is compared with conventional current control with RSVPWM and given in Table 1. PWM switching signals are creating harmonic content around carrier frequency. The voltage spectrum of DMPC method is characterized by discrete lines and these lines are spread over the frequency range. The switching frequency for predictive control is variable and switching state of the inverter can be changed only once during each sampling instant and frequency is limited to half the sampling frequency. But the switching states do not change at every time so average frequency does not change.

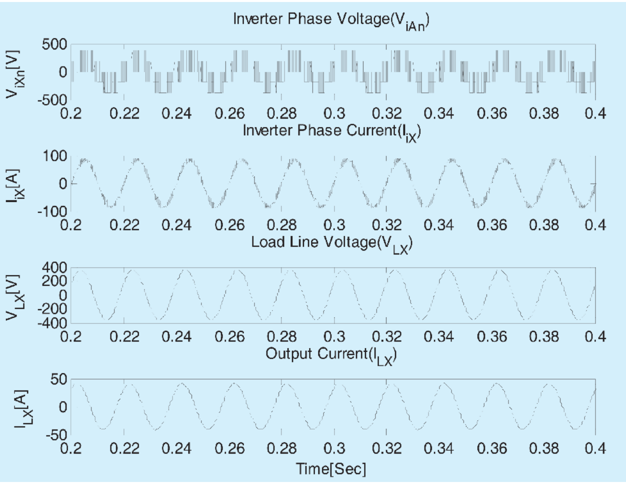

FIG. 6 SIMULATION RESULTS OF THE CONVENTIONL CURRENT CONTROLLER

The DMPC control scheme is based on control theory and it is not more complex thanthe conventional control scheme with PI regulator based SVPWM. In PI regulator based control scheme, voltage vectors are used for implementation. But in the case of DPMC, voltage vectors are used as finite set of possible actuations and DPMC use predictions for each voltage vector using in discrete time model. In case of conventional current controller, to get the proper result, k_p and k_i values need to be adjusted. In the case of DPMC cost function is used for analysis. Table 1 shows comparison of conventional current controller and DMPC.

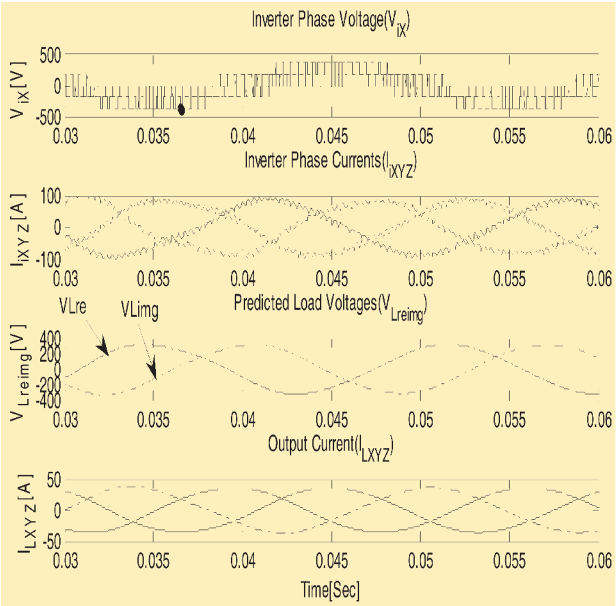

FIG. 7 SIMULATION RESULTS OF THE MODEL PRECDETIVE CURRENT CONTROLLER

TABLE 1

COMPARSION TWO METHODS

Current Controller with RSVPWM	DMPC
PWM switching model for Inverter, Controller model is required	Load and Inverter model for prediction
Controller Parameters are necessary to vary based on required output	Minimization of Cost Function
PWM (SVPWM) circuit is required	No Modulation circuit is required
Switching frequency is fixed	Switching frequency is controllable
Both Analog and Digital Implementation	Only Digital Implementation

5.0 CONCLUSIONS

In this paper, a current control technique with RSVPWM and DMPC techniques are presented and performance analyses of two techniques are compared. First mathematical modeling of the 3-phase VSI is derived and current controller with RSVPWM is explained. DMPC controller with LC filter and load is modeled and selecting cost function was explained. Both techniques are simulated using MATLAB/Simulink tool. Operating principles and simulation results shows that conventional controller based technique is on required output and it is varying when parameters are changes, but in the case of DMPC cost function should be reduced. In DMPC controller, no PWM circuit is required and switching frequency is controllable and very easy to implement in digital domain. Finally DMPC technique does not require any parameter adjustment and there is no cascaded control structure in it.

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