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DESIGN AND ANALYSIS OF MODEL PREDICTIVE VOLTAGE AND CURRENT CONTROLLERS FOR THREE PHASE VOLTAGE SOURCE INVERTER IN MICRO GRID

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ABSTRACT

Nowadays renewable energy sources are essential to meet the real power demand. All the Distributed Energy Resources are connected to the common grid through three phase Voltage Source Inverter (VSI). The reliable operation of microgrid can be achieved by controlling three phase voltage source inverter. Voltage and frequency of the Distributed Energy Resources are continuously varying and they depend on nature. While interfacing Distributed Energy Sources to the common grid, both variables must be maintained constant. And these variables are controlled by controlling three phase voltage Source Inverter. The two loop model predictive current and voltage controller is proposed in this paper for voltage source inverter operation. The outer voltage control loop is for controlling frequency and voltage which gives reference input to the inner loop model predictive current controller. The inner current loop generates signal to regulate the inverter current. The Space Vector Pulse Width Modulation Signal Generator is used for voltage commands. The performances of the both controllers are analyzed for various load conditions. Simulation is carried out in MATLAB.

Keywords: model predictive voltage, current controller, space vector, pulse width modulation, voltage source inverter, microgrid.

1. INTRODUCTION

Renewable energy sources like solar, wind, fuel cell and etc. are playing significant role to meet the real power demand in energy sector. Now a day's customers are able to generate energy using renewable sources and they are connected to common grid. The energy from the renewable sources like solar and wind is variable and it depends on temperature or wind force respectively. So customer may either generate or absorb the real power. This stimulates the power flow between main grid and customer in either direction. When customers are connected to the common grid, complex power system network is disturbed. Penetration of renewable sources introduced the problem such as power quality, reliability, storage and accommodation of Distributed Generation (DG). Power system network should be protected from mal operation and instability by self – healing. This process must be very fast to avoid unstable operation [1].

Energy from Distributed Energy Resources (DERs) is penetrated to microgrid through three VSI [2]. VSI can easily control the voltage and frequency of the supply. So VSI plays important role in energy sector [3]. Controlling of voltage and frequency with power balance of a micro grid is nonlinear problem. So designing the controller for VSI is the main task to control the variables regardless of load variation [4-7]. If voltage and frequency of Distribution Generation (DG) unit is assumed as linear, problem associated with large variation of load are not able to resolve. So the converter must be provided with controller for improving performance of the system by proper controlling voltage and frequency.

Three phase inverter operations can be controlled by PID controller, fuzzy controller, hysteresis current controller, sliding mode controller and model predictive controller [8]. PID controller response is slow. So there is a possibility for changing the system state to unstable during large variations [9]. Dimensionality and tuning are the main drawbacks of fuzzy controllers [10].

Recently, PWM based power electronics converters are controlled by using Model Predictive Control strategy. MPC has more advantage than other controller. It reduces harmonic. It gives better static and dynamic performance. MPC works based on future behavior of the variables in time horizon. The variables are optimized by minimizing the cost function. MPC are used in various power system applications. Some of the applications are economic dispatch [11], minimization of emission [12], maintenance scheduling [13], dynamic optimum dispatch [14], and voltage regulation of DG [15]. MPC can be used for voltage control [16] or current control of inverter [17].

This paper proposes controllers for PWM inverter to regulate both voltage and frequency. For the Simulation, islanded microgrid with different loading are considered. The inner loop MPC is used to limit the inverter current during overload or fault condition. The outer loop MPC is used for regulating the voltage at the load terminal. This method gives better performance and less harmonic.

THREE PHASE VOLTAGE SOURCE INVERTER

Figure-1 shows three phase PWM inverter interfaced with DER units in microgrid. Since DERs unit give DC supply, constant DC Source has been used. A standard three phase inverter with MOSFET switches is used. LC filter is used to reduce the harmonics which is present in the output of inverter. Three phase inverter and utility grid are interfaced through delta – wye isolation

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transformer. This transformer is also act as voltage transformer. Small capacitors are connected to reduce the harmonic on load side and are stabilizing the gird voltage.

Space Vector Pulse Width Modulation Generator (SVPWM) is used to generate the gate pulses for three phase VSI and according to the command signal output voltage is controlled. SVPWM requires signal in dq0 frame. So the state space model of the system is developed in abc frame and it is converted to dq frame by using park's transformation. State variable equations are derived by using Kirchhoff's voltage and current laws. State variables are voltage and current in abc frame.

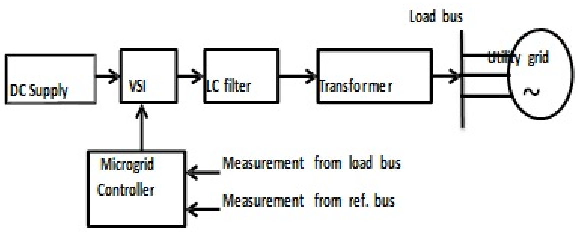

Figure-1. Three phase PWM inverter interfaced with microgrid.

$$\frac{d\vec{V}_{abc}}{dt} = \frac{1}{3C_{inv}}\vec{I}_{abc} - \frac{1}{3C_{inv}}.T_{ri}.\vec{I}_{sdabc} \quad (1)$$

$$\frac{d\vec{I}_{abc}}{dt} = \frac{1}{L_{inv}}\vec{V}_{pwm_{abc}} - \frac{1}{L_{inv}}.\vec{V}_{abc} \quad (2)$$

$$\frac{d\vec{V}_{0abc}}{dt} = \frac{1}{C_{Load}}.\vec{I}_{sdabc} - \frac{1}{C_{load}}\ \vec{I}_{load_{abc}} \quad (3)$$

$$\frac{d\vec{I}_{sd_{abc}}}{dt} = \frac{-R_T}{L_T}\vec{I}_{sd_{abc}} + \frac{1}{L_T}.T_{ri}.\vec{V}_{i_{abc}} - \frac{1}{L_T}.\vec{V}_{load_{abc}} \quad (4)$$

Where vector I_{abc} , and V_{abc} are inverter current and voltage respectively. I_{0abc} , and V_{0abc} are grid or load current and voltage respectively. V_{pwmabc} is PWM voltage in abc frame. I_{sdabc} is secondary current of the transformer in abc frame. All the state variable equations are in abc frame which are converter into the dq frame by using transformations matrix. The transformations matrix of transformer current equation is T_{ri} and voltage equation is T_{rv}.

$$T_{rv} = t_r\begin{bmatrix} 1 & -2 & 1 \\ 1 & 1 & -2 \\ -2 & 1 & 1 \end{bmatrix}, T_{ri} = t_r\begin{bmatrix} 0 & 0 & -1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix}$$

Where t_r is the transformation ratio of the transformer. The state variable equations in dq0 frame [18] are

$$\vec{V}_{dq0} = K_s\vec{V}_{abc}, \qquad \vec{I}_{dq0} = K_s\vec{I}_{abc}$$

Where $\vec{V}$ can be $\vec{V}_i$, $\vec{V}_{load}$, and $\vec{V}_{pwm}$, $\vec{I}$ can be $\vec{I}_i$, $\vec{I}_{load}$, and $\vec{I}_{sd}$ and K_s is the transformation matrix and

$$K_s = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Since the system assumed as balanced, zero sequence current and zero sequence voltage will be zero. So zero sequence current and voltage are eliminated in modeling. Using the transformation equations and transformation matrix, state variable equation in abc frame is converted to dq stationary reference frame and are written as

$$\frac{d\vec{V}_{dq}}{dt} = \frac{1}{3C_{inv}}\vec{I}_{dq} - \frac{1}{3C_{inv}}.T_{rvqd}.\vec{I}_{sd_{dq}} \quad (5)$$

$$\frac{d\vec{I}_{dq}}{dt} = \frac{1}{L_{inv}}\vec{V}_{pwm_{dq}} - \frac{1}{L_{inv}}.\vec{V}_{dq} \quad (6)$$

$$\frac{d\vec{V}load_{dq}}{dt} = \frac{1}{C_{Load}}.\vec{I}_{dq} - \frac{1}{C_{load}}\ \vec{I}_{load_{dq}} \quad (7)$$

$$\frac{d\vec{I}_{sd_{dq}}}{dt} = \frac{-R_T}{L_T}.\vec{I}_{sd_{dq}} + \frac{1}{L_T}.T_{riqd}.\vec{V}_{i_{dq}} - \frac{1}{L_T}.\vec{V}_{load_{dq}} \quad (8)$$

Where

$$T_{riqd} = \frac{3}{2}t_r\begin{bmatrix} 1 & \sqrt{3} \\ -\sqrt{3} & 1 \end{bmatrix},$$

$$T_{rvqd} = \frac{1}{2}t_r\begin{bmatrix} 1 & -\sqrt{3} \\ \sqrt{3} & 1 \end{bmatrix}$$

The state variable model of eqns (5) to (8) is rewritten by

$$\dot{x} = A_s x + B_s u + E_s d \quad (9)$$

$$y = C_s x + D_s u \quad (10)$$

Where x, u, d and y are state variable, input variables, disturbance variables and output variables matrix respectively and are

$$x = \begin{bmatrix} V_{iq} & V_{id} & I_{i_q} & I_{i_d} & V_{loadq} & V_{loadd} & I_{sd_q} & I_{sd_d} \end{bmatrix}^T$$
$$u = \begin{bmatrix} V_{pwm_q} & V_{pwm_d} \end{bmatrix}^T;$$
$$y = \begin{bmatrix} V_{load_q} & V_{load_d} \end{bmatrix}^T;$$
$$d = \begin{bmatrix} I_{load_q} & I_{load_d} \end{bmatrix}^T;$$

2. DESIGN OF MICROGRID CONTROLLERS

In this model, two controllers are used for controlling the microgrid variable such as current and voltage. The inner loop model predictive controller controls the inverter currents during overload and fault condition. The outer loop model predictive controller controls load voltage or inverter output voltage. System frequency is assumed as 50Hz.

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The outer loop voltage controller generates set value for inverter current and inner current controller generates PWM voltage signal to regulate the inverter current to the set values. Figure-2 represents block diagram of the control structure of inverter.

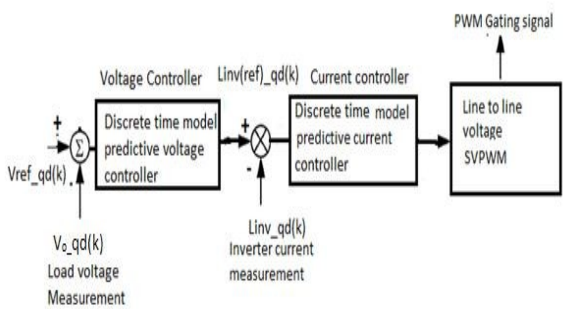

Figure-2. Proposed model predictive voltage/ current control.

a) Model predictive current controller

Model Predictive Control along with Voltage Source Inverter is given by Figure-3.

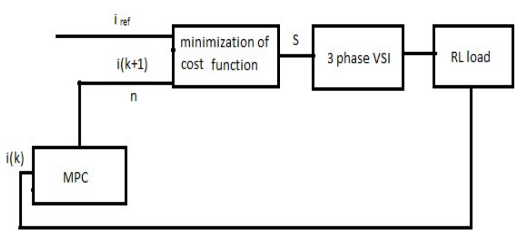

Figure-3. Block diagram of model predictive control for VSI.

Where i_{ref} represents reference current for the predictive current controller. i(k) is the load current measured at time k. i(k+1) is the value from the predicted current of m states for all possible n switching states at time k+1. The difference between reference and predicted values are minimized by using cost function. This minimizes no. of switching state and optimized switching signal.

In one prediction step, eight different switching states are possible. To minimize the complexity, best seven voltage vectors are chosen initially. After that one of optimum vector is determined, this will give the best switching state. In order to determine best one, all the seven vectors should be applied to the next sampling time at k+1.

The control algorithm of model predictive control is given below.

i. Measure the load currents.

ii. Predict the load currents for the next sampling period.

iii. Estimate the cost function for each prediction

iv. Optimum switching state is selected which gives less cost.

v. Apply the new switching state.

Flow chart representation of the algorithm is given in Figure-4. In the current control, error between predicted current and reference current is applied to the cost function and cost function is minimized.

Discrete time Model predictive control is having the advantage of fast and non – overshoot response. So Discrete MPC is used for inner current controller. The continuous model of inverter with LC filter is alone taken for controller design.

The continuous model is linearized to obtain discrete model. Transformer and load are not considered. But secondary current of transformer is treated as disturbance variable. The state space model of the system used for the controller design is eqn (5) and (6). The discrete model of state space equation is given below.

$$\dot{x} = A_1 x + B_1 u + E_1 d \qquad (11)$$

$$y = C_1 x + D_1 u \qquad (12)$$

Where x, u, d, and y are state variable, input variable, disturbance variable and output variable respectively.

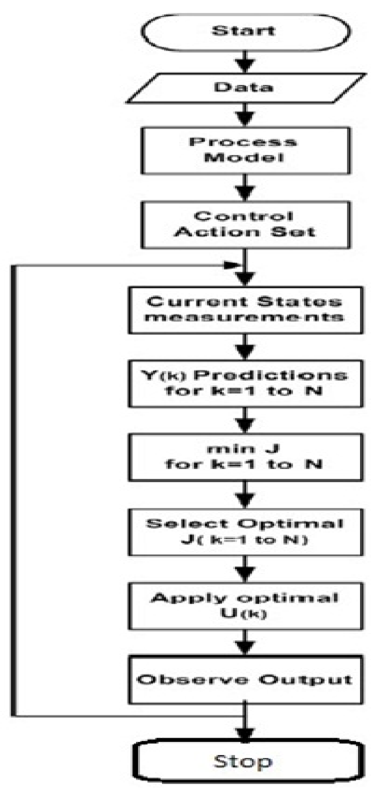

Figure-4. Flow chart for model predictive control.

$$x = [V_{t_q} \ V_{t_d} \ I_{t_q} \ I_{t_d}]^T$$

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$u = [V_{pwm_q} \quad V_{pwm_d}]^T;$

$y = [i_q \quad i_d]^T;$

$d = [I_{sd_q} \quad I_{sd_d}]^T;$

The continuous state model (11) and (12) are transformed to discrete form and given in (13) and (14).

$$x_1(k+1) = A_1^* x_1(k) + B_1^* u_1(k) + E_1^* d_1(k) \quad (13)$$

$$y_1(k) = c_1^* x_1(k) + d_1^* u_1(k) \quad (14)$$

b) Discrete model of model predictive voltage control

Model predictive voltage controller is the outer loop. So the plant viewed from the voltage controller is the combination of three phase inverter with LC filter, transformer and discrete current controller. The following discrete state model is used for designing the voltage controller. Eqns (15) and (16) are representing discrete model.

$$x(k+1) = A_2^* x(k) + B_2^* u(k) + E_2^* d(k) \quad (15)$$

$$y(k) = c_2^* x(k) + d_2^* u(k) \quad (16)$$

Where state variable, input variable, output and disturbance variables are

$x = [V_{tq} \quad V_{td} \quad I_{t_q} \quad I_{t_d} \quad V_{loadq} \quad V_{loadd} \quad I_{sd_q} \quad I_{sd_d}]^T;$

$u = [V_{pwm_q} \quad V_{pwm_d}]^T;$

$y = [V_{o_q} \quad V_{o_d}]^T;$

$d = [I_{o_q} \quad I_{o_d}]^T;$

4. SPACE VECTOR PULSE WIDTH MODULATION

This modulation is used to generate required output voltage vector in dq stationary reference frame. Eight switching pattern are possible for three phase voltage source inverter and each pattern determine a voltage space vector.

Voltage space vector of three phase Voltage source inverter is given in Figure-5. All eight voltage space vector (V_0 to V_7) are represented. Voltage vector, V_0 and V_7 are giving zero magnitude. The remaining vectors ($V_{1\ to}$ V_6) are having equal magnitude and is (2/3) V_{dc}. Grid angle indicating the relative position of the d - axis to the A – axis and phase angle of the reference voltage vector will decide reference voltage vector position.

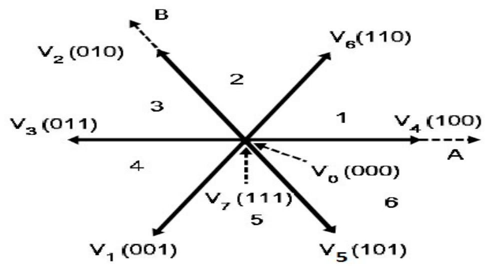

Figure-5. Eight voltage space vector for three phase VSI.

In order to minimize the current harmonics and to minimize switching time and loss, the reference voltage space vector is produced by the neighboring vector of the located segment in SVPWM. Fig. 6 describes synthesizing procedure in sector 1.

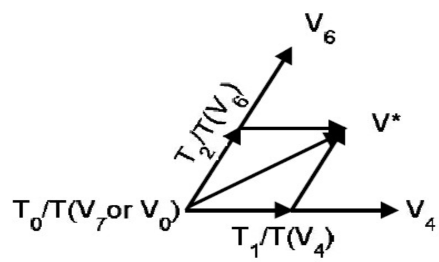

Figure-6. Synthesizing of voltage vector using neighboring vector.

T represents PWM period. In each PWM cycle, there is two active vectors. The time durations of two active vectors in each PWM cycle are represented by T_1 and T_2. Zero active vector time duration is T_0 and is equal to (T – T_1 -T_2). After finding T_1, T_2, and T_0, three phase PWM pulses are generated by symmetrical method.

In one carrier period, only one switch component is used and others are brought to fixed switching frequency. So the entire voltage space vector is divided into ripple frequency to the double of switching frequency.

5. RESULTS

Three phase voltage source inverter with model predictive voltage and current controller is simulated in MATLAB/Simulink. Performance of voltage controller is tested by changing the reference voltage and Current controller is checked by varying the load resistance. The performance and robustness of both the controllers are verified. Total harmonics are measured by FFT analysis.

Case-1

In this case, effectiveness of voltage controller is verified. Simulation is carried out for for 1sec. At time t=0, reference voltage is 100V. After 0.4 sec reference voltage is changed to 120V. Again reference voltage is reduced to 0.6 sec. In both the switch over period voltage is quickly stabilized with zero frequency error. Load

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resistance is maintained as 20Ω. The results are shown in Figure-7.

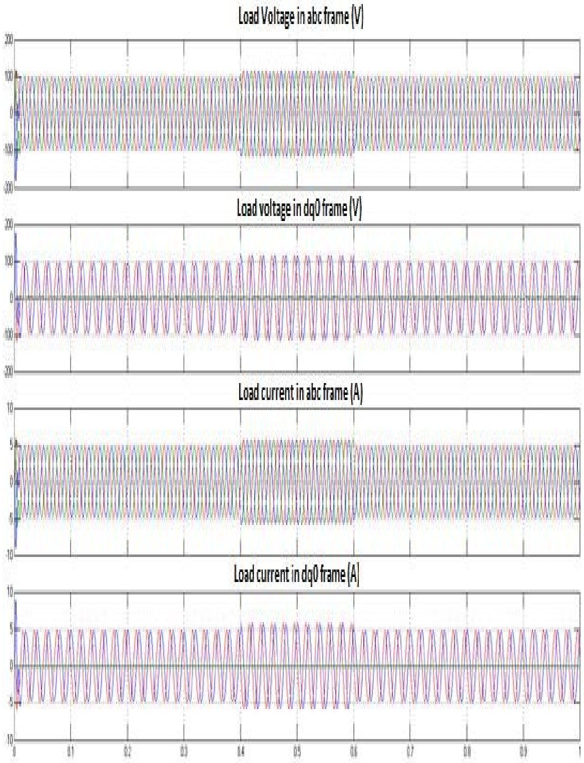

Figure-7. Load voltage and current with variation of dq reference voltage.

Case-2

In this case, the effectiveness of current controller is tested. Current controller is regulating the current during overload condition. So the load resistance is gradually increased from 10Ω. When t=0.5 sec, load resistance is increased to 20Ω and at time t=0.7sec load resistance is increased to 40Ω. When load resistance increases, VSI decrease the current to compensate the real power of the load. This is shown in Figure-8.

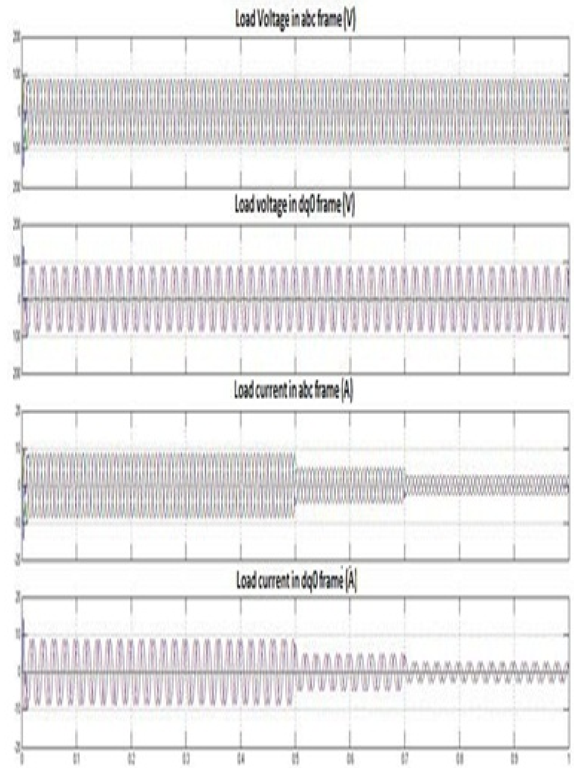

Figure-8. Load voltage and current with variation of load resistance.

5. CONCLUSIONS

Three phase inverter with model predictive voltage and current controller is presented in this paper. Both the controllers are in cascade. Total harmonic distortion factor is 4.33% for reference voltage variation (case-1) and 5.13% for load resistance variation (case-2). Both the cases frequency error is zero. This shows that controllers response is very fast and stability is also maintained. Voltage and frequency are maintained constant irrespective of load resistance variation.

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