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Model Predictive Control of Distributed Generation Inverter in a Microgrid

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Abstract—This paper presents a new control method to regulate various parameters such as voltage, current and power of the inverter interfaced with Distributed Generation (DG) in a microgrid. Model Predictive Control (MPC) is used to control the inverter of the DG using a state-space model of the inverter based microgrid. The operation of the microgrid is tested under grid-connected and stand-alone conditions. MATLAB/Simulink is used to simulate the proposed microgrid under these two operating conditions. Simulation results show that the DG inverter can operate effectively with MPC in the microgrid to provide the desired voltage, current and power under grid-connected and stand-alone conditions.

Index Terms—Microgrid, distributed generation, inverter, model predictive control.

I. INTRODUCTION

Microgrid is an integrated energy system consisting of a low-voltage distribution network with distributed generations (DGs) such as solar photovoltaics (PVs), microturbines and fuel cells together with power converters, energy storage devices, and customer loads. There is an increased penetration of DGs in the power grid. These DGs provide variable DC or AC output voltage and thus require inverters or rectifiers to interface them with the microgrid [1].

Inverter control has been widely applied in microgrids, energy storage systems and uninterruptible power supplies (UPSs). Several control methods such as linear, sliding mode, artificial intelligence and predictive control have been used for the control of inverters in microgrids operating under various conditions [2], [3]. Predictive control has been gaining increased attention in recent years due to its significant advantages over other classical control methods. The main principle of predictive control is the use of a system model in order to predict the future behavior of the controlled variables. Then the controller uses this information to obtain the optimal control input, based on a predefined optimization of a cost function. Several predictive control methods, namely deadbeat control, generalized predictive control (GPC) and model

predictive control (MPC) are available [4].

A microgrid is able to operate efficiently under both grid-connected (GC) as well as stand-alone (SA) conditions. So an effective control method is needed to provide the desired voltage and power to the load under both these conditions. In GC condition, inverter voltage cannot be regulated as inverter is tied to the grid voltage and frequency. In this condition, the inverter current is controlled to inject a preset amount of power into the grid [5]. In SA condition, the inverter output voltage is controlled to provide the required power to the load [6]. In this paper, a control method called model predictive control (MPC) is used to control the output voltage and real and reactive power of the inverter. A state-space model of the inverter is used to predict the future behavior of the variables such as voltage and current. The main advantages that make MPC suitable for the control of inverters are:

- Easy inclusion of non-linearities in the model as inverters are generally non-linear systems with a finite number of switching devices and simple treatment of constraints, such as maximum output voltage of the inverter, maximum current etc.
- No need of any modulator and gate drive signals as the inverter switching signals are generated directly by the controller itself.

One disadvantage of using MPC is the need of huge number of calculations. However with the advent of faster and powerful computers, there has been an increase in the application of this method. In [7]-[11], MPC is used to control an inverter but the different modes of operation of the inverter in a microgrid such as GC and SA modes have not been addressed.

Different from other methods, a new state-space model based MPC approach is used in this paper to regulate the inverter during its different modes of operation. Finally simulation studies are conducted on the proposed microgrid to test the effectiveness of its operation during GC mode as well as SA mode.

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Figure 1. Configuration of the proposed microgrid.

II. SYSTEM DESCRIPTION

The proposed microgrid system comprises a PV array as the main DG unit, which is connected in parallel to the dc side of the DG inverter through a dc/dc boost converter. V_{dc} is the value of the DC link voltage of the DG inverter. A lithium ion storage battery, which is used to back up the intermittent generation of the PV array, is also connected to the dc side of the DG inverter through a bidirectional dc/dc buck-boost converter. There are two semiconductor switches in each of the three legs of the three-phase inverter shown in Fig. 1. An LC filter is connected to each phase of the inverter, where L and C represent the inductance and capacitance of the filter respectively. R represents the inverter power loss resistance. The inverter along with the filter is connected to a load as well as the utility grid. In Fig. 1, R_L and L_L are the resistance and inductance of the load respectively.

The inverter is connected to an LC filter to smoothen the inverter output currents. The currents flowing through the filter in each phase are represented by i_a , i_b and i_c . The output currents of the inverter in each of the three phases are represented by $i_{DG,a}$, $i_{DG,b}$ and $i_{DG,c}$. The currents supplied by the grid in each of the three phases are represented by i_{Ga} , i_{Gb} and i_{Gc} respectively. The load currents in each of the three phases are represented by i_{La} , i_{Lb} and i_{Lc} . Voltages across the load in each of the three phases are represented by V_{La} , V_{Lb} and V_{Lc} .

In case of a fault in the grid, a circuit breaker (CB) is used to disconnect the microgrid from the utility grid. The microgrid is now operated in the islanded mode. Under GC condition, the currents - $i_{DG,a}$, $i_{DG,b}$ and $i_{DG,c}$ are regulated to their specified reference values in order to provide a preset power to the load. So the inverter and grid can share the load demand during the GC condition.

During SA operation, the inverter in the microgrid is required to supply for all the load power demand. So under the

SA condition, the inverter can regulate its output voltage across the load in each of the three phases as shown in Fig. 1. This is done in order to provide the required amount of reliable power to the load. The switches (S_1 , S_2 , S_3 , S_4 , S_5 and S_6) of the inverter have two operating states and can be defined as follows:

$$u_i = \begin{cases} 1, & \text{switch } S_i \text{ is ON} \\ 0, & \text{switch } S_i \text{ is OFF} \end{cases} \quad (1)$$

where $i = 1, 2, 3, 4, 5, 6$.

The switching states of the semiconductor switches are controlled separately in each of the three phases. Here we assume a balanced three-phase system. The filter and load impedances remains the same in all the three phases of the system. There are mainly two modes of operation of a microgrid, namely GC and SA modes of operation. In GC mode, the grid as well as the DG supplies the required power to the load. Hence it is necessary to develop a suitable control strategy to control the output power of the DG during this mode. During the transition from GC to SA mode, the DG can respond effectively with minimum delay to switch over from GC to SA mode. In SA mode, the DG can regulate the load voltage to provide the required real and reactive power to the load.

In the proposed microgrid, an RL load is considered. The proposed control method can also be applied to the same microgrid with purely resistive load as well. The load voltage, the inverter output current, real and reactive power and also the real and reactive power consumed by the load are analyzed in the GC mode first. Then the load voltage and inverter output current are analyzed during the transition from GC to SA mode. In addition, the real and reactive power consumed by the load is also analyzed during SA mode.

III. INVERTER MODELLING AND CONTROL

A microgrid should be able to provide its load with specified voltage, current and power during both GC and SA modes. Thus effective strategies are developed in this paper to control the DG inverter during both GC and SA modes.

A. Control of Inverter During GC Mode

When the microgrid is connected to the grid, the microgrid voltage and frequency is tied to that of the utility grid and thus remains fixed. In order to make the inverter in the microgrid provide specified power to the load, the output current of the inverter needs to be controlled. This mode of inverter operation is called Current Control Mode (CCM). The single-phase equivalent circuit of the inverter based microgrid in the GC mode is shown in Fig. 2. By applying Kirchhoff's law to the single phase equivalent circuit, the following equations are obtained:

$$u_1 V_{dc} = R i_a + L \frac{di_a}{dt} + V_{La} \quad (2)$$

$$C \frac{dV_{La}}{dt} = i_a - i_{DG,a} \quad (3)$$

Euler difference method is applied to (2) and (3) to derive the augmented form of the discrete state-space model as follows:

$$x_c(k+1) = A_c x_c(k) + B_c \Delta u_c(k) + D_c \Delta \omega_c(k) \quad (4)$$

$$y_c(k) = C_c x_c(k) \quad (5)$$

where

$$A_c = \begin{pmatrix} 1 - (RT_s/L) & 0 \\ 1 - (RT_s/L) & 1 \end{pmatrix}; B_c = \begin{pmatrix} V_{dc}T_s/2L \\ V_{dc}T_s/2L \end{pmatrix}$$

$$C_c = (0 \ 1); D_c = \begin{pmatrix} 0 & 0 & -T_s/L \\ -C/T_s & C/T_s & -T_s/L \end{pmatrix}$$

$$x_c(k+1) = \begin{pmatrix} \Delta i_a(k+1) \\ i_{DG,a}(k+1) \end{pmatrix}; x_c(k) = \begin{pmatrix} \Delta i_a(k) \\ i_{DG,a}(k) \end{pmatrix}$$

$$\Delta u_c(k) = \Delta u_1(k); \Delta \omega_c(k) = \begin{pmatrix} \Delta V_{La}(k+2) \\ \Delta V_{La}(k+1) \\ \Delta V_{La}(k) \end{pmatrix}$$

$$y_c(k) = i_{DG,a}(k)$$

$x_c(k)$ is the state vector, $y_c(k)$ is the output vector, $\Delta u_c(k)$ is the incremental change in the switching state input vector, T_s is the discrete sampling time period, k is the sampling instant, $x_c(k+1)$ is the state vector at the sampling instant $k+1$ and $y_c(k+1)$ is the output vector at the sampling instant $k+1$.

Figure 2. Single-phase equivalent circuit of the microgrid in GC mode.

The input constraint and input increment constraint are as follows:

$$0 \leq u_1 \leq 1; -1 \leq \Delta u_1 \leq 1$$

The MPC algorithm generates the control input switching signals by minimizing the objective function to track the reference output R_s . The objective function is as follows

$$J = (R_s - Y)^T (R_s - Y) + \Delta U^T R \Delta U \quad (6)$$

where

$$R_s = (1 \ 1 \dots 1 \ 1) r(k)$$

$$Y = (y(k+1) \ y(k+2) \ y(k+3) \dots \ y(k+N_p))^T$$

$$\Delta U = (\Delta u(k) \ \Delta u(k+1) \ \Delta u(k+2) \dots \ \Delta u(k+N_c-1))^T$$

$r(k)$ is the desired output signal and Y is the actual output. The number of 1's in the above matrix R_s is equal to N_p , which is the prediction horizon used for MPC. The matrix R is a diagonal matrix in the given form as follows:

$$R = r_w I_{N_c \times N_c} \quad (7)$$

where r_w is used as a tuning parameter for the desired closed-loop performance. I is the identity matrix. N_c is the control horizon used for MPC.

B. Control of Inverter During SA Mode

When the grid is disconnected, the load voltage is disturbed. This will affect the operation of the microgrid. The load voltage needs to be maintained at the required nominal value to ensure the reliable operation of the load. Thus the inverter controller is made to switch over from GC mode to SA mode of operation to maintain the load voltage constant. As a result, the DG inverter is operated to maintain the required load voltage and thereby supply the required power to the load. This mode of operation of the inverter is called Voltage Control Mode (VCM). The single-phase equivalent circuit of the inverter based microgrid in the SA mode is shown in Fig. 3. Since the grid is disconnected during SA mode, it is not shown in Fig. 3. By applying Kirchhoff's law to the single phase equivalent circuit, the following equations are obtained:

$$u_1 V_{dc} = R i_a + L \frac{di_a}{dt} + V_{La} \quad (8)$$

$$C \frac{dV_{La}}{dt} = i_a - i_{La} \quad (9)$$

Due to high sampling frequency, it can be assumed that

$$\frac{di_{La}}{dt} = 0 \quad (10)$$

Euler difference method is used to derive the discrete time state space model as follows:

$$X(k+1) = A_d X(k) + B_d U(k) \quad (11)$$

$$Y(k) = C_d X(k) \quad (12)$$

where

$$X(k) = \begin{pmatrix} i_a(k) \\ V_{La}(k) \\ i_{La}(k) \end{pmatrix}; U(k) = u_1(k)$$

$$Y(k) = V_{La}(k)$$

$$A_d = \begin{pmatrix} 1 - RT_s/L & -T_s/L & 0 \\ T_s/C & 1 & -T_s/C \\ 0 & 0 & 1 \end{pmatrix}; B_d = \begin{pmatrix} V_{dc} T_s / 2L \\ 0 \\ 0 \end{pmatrix}$$

$$C_d = (0 \quad 1 \quad 0)$$

$X(k)$, $U(k)$ and $Y(k)$ are the state, input and output vectors respectively. The augmented form of the discrete state space-model is obtained as follows:

$$x_e(k+1) = A_e x_e(k) + B_e \Delta u_e(k) \quad (13)$$

$$y_e(k) = C_e x_e(k) \quad (14)$$

where

$$x_e(k+1) = \begin{pmatrix} \Delta X(k+1) \\ Y(k+1) \end{pmatrix}; x_e(k) = \begin{pmatrix} \Delta X(k) \\ Y(k) \end{pmatrix}$$

$$A_e = \begin{pmatrix} A_d & 0_{3 \times 1} \\ C_d A_d & 1 \end{pmatrix}; B_e = \begin{pmatrix} B_d \\ C_d B_d \end{pmatrix}; C_e = (0 \quad 0 \quad 0 \quad 1)$$

$$y_e(k) = V_{La}(k)$$

$$\Delta u_e(k) = \Delta u_1(k)$$

Figure 3. Single-phase equivalent circuit of the microgrid in SA mode.

$x_e(k)$, $\Delta u_e(k)$ and $y_e(k)$ are the state, input and output vectors respectively in the augmented model at the sampling instant k . Similarly, $x_e(k+1)$, $\Delta u_e(k+1)$ and $y_e(k+1)$ are the state, input and output vectors respectively at the sampling instant $k+1$. The constraints and objective function in GC mode are similar to that in SA mode, except that the output vector chosen in GC mode is output current of the inverter, while in SA mode, the output vector chosen is the load voltage.

IV. SIMULATION STUDIES

MATLAB/Simulink is used to simulate the microgrid for two test cases. The microgrid is operated under GC mode in the first test case. In the first test case, DG needs to provide the required amount of power to the load. When the grid is disconnected from the microgrid, there should be a smooth transition from GC to SA mode to minimize any sudden voltage change across the load [12]. Both the test cases are explained as follows:

A. GC mode

In the GC mode, the desired amount of real and reactive power to be provided by the DG to the load is set as the reference values. The inverter output voltage is same as the grid voltage in the GC mode. Since the three-phase microgrid is assumed to be a balanced system, the output currents in each phase of the inverter remain the same. The parameters used in the simulation are given in Table I.

TABLE I. PARAMETERS OF THE PROPOSED SYSTEM

Parameters	Value
DC source voltage	$V_{dc} = 325.2 \text{ V}$
Inverter power loss resistance	$R = 0.001 \Omega$
Filter inductance	$L = 1.2 \text{ mH}$
Filter capacitance	$C = 20 \mu\text{F}$
Load resistance	$R_L = 10 \Omega$
Load inductance	$L_L = 10 \text{ mH}$
Sampling period	$T_s = 0.5 \mu\text{s}$
Frequency	$f = 50 \text{ Hz}$

The values of reference real and reactive power output/phase of the inverter chosen are: $P=1000 \text{ W}$; $Q= 1000 \text{ VAR}$. The total three-phase real and reactive power output of the inverter is 3000 W and 3000 VAR respectively. Power factor and reference output current/phase of the inverter are calculated as follows:

$$\text{Power factor (pf)} = P / \sqrt{P^2 + Q^2} = \cos 45^\circ = 0.707$$

$$\text{Reference Output current/phase} = 1.414 \times P / (230 \times \text{pf}) = 8.3 \text{ A (peak)}$$

Figure 4. Three-phase load voltage.

Figure 5. Three-phase inverter output current.

Figure 8. Three-phase load voltage.

Figure 9. Three-phase inverter output current.

Figure 6. Real power output waveforms.

Figure 10. Real and reactive power consumed by the load.

Figure 7. Reactive power output waveforms.

As shown in Fig. 4, the peak value of the load voltage obtained is equal to 325.2 V, which is same as the DC source voltage. As shown in Fig. 5, the peak value of the inverter output current is equal to 8.3 A, which is same as the calculated value.

As shown in Fig. 6, the value of the reference real power output of the three-phase inverter is maintained at 3000 W. The real power consumed by the load is 14450 W, which is equal to the sum of the real power supplied by the inverter and the grid. The real power delivered by the grid is equal to 11450 W. In Fig. 7, it is seen that the value of the reference reactive power output of the three-phase inverter is maintained at 3000 VAR. The reactive power consumed by the load is 4500 VAR, which is equal to the sum of the reactive power supplied by the inverter and the grid. The reactive power delivered by the grid is equal to 1500 VAR.

B. Transition from GC to SA mode

Initially the microgrid operates in GC mode. At $t = 0.035$ s, the grid is disconnected. As shown in Figs. 8 and 9, MPC ensures a rapid transition of the microgrid from GC to SA mode, except for minor transient disturbances in load voltage and inverter output current for a very short time duration of about 0.005s.

After this transient period, the load voltage and inverter output current attains a steady state value. The output current of the inverter increases to 31.03 A (peak) in SA mode, as shown in Fig. 9. The real and reactive power consumed by the load in SA mode is shown in Fig. 10.

The amplitude of the reference output voltage of the inverter is maintained at 325.2 V (peak) in SA mode as shown in Fig. 8, to ensure the required power delivery to the load as shown in Fig. 10. Thus the microgrid is capable of stable and reliable operation both in GC as well as in SA mode.

V. CONCLUSION

A new state-space model based MPC approach has been proposed for the control of a three-phase inverter, which is connected to a DG in the proposed microgrid. The microgrid is tested under both GC and SA modes of operation. The proposed MPC makes use of the model of the inverter to control parameters like voltage, current and power of the DG. The simulation results have shown that the proposed approach achieves good performance on both current-reference tracking in GC mode and voltage-reference tracking in SA mode. With the help of the newly developed control strategy, the proposed microgrid is able to operate efficiently and accurately during both GC and SA modes. To reduce the transient disturbances in the load voltage and improve the load voltage profile during the transition from GC to SA mode, the use of battery energy storage system on the ac side of the DG inverter can be considered, which will have a scope for further research.

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