Cooperative Model Predictive Control for Distributed Photovoltaic Power Generation Systems using Dynamic Matrix Control

Aishwarya Shinde

Abstract- In this paper, we examine a cooperative model predictive control for distributed photovoltaic (PV) power generation systems using Dynamic Matrix control(DMC). The proposed control strategy not only makes all the distributed PV generators converge and operate at the same ratio of the available power, but also regulates the total power output of all the PV generators to ensure the stability of the distributed power generation systems. Simulation results on case study of the 4-machine 14-bus distributed power generation test system are provided to verify the validness and effectiveness of the proposed control strategy.

Index Terms- Photovoltaic (PV), Dynamic Matrix control(DMC), Model Predictive Control(MPC) Kirchhoff's current law (KCL) constant voltage and frequency (V/f).

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I. INTRODUCTION

In recent years, renewable energy sources such as wind, solar, and hydro, which are both environmental and renewable, have attracted our attentions [1]. Solar energy as one of the main renewable energies has been used to produce electricity by solar PV generators which convert sunlight directly into electricity using photovoltaic cells. There are two types of solar power generation systems. One is off-grid solar power generation system which works independently. The other is grid-connected solar power generation system which is connected to electrical grid [2],[3],[4],[5]. In the last few years, there have been an increasing number of PV generators integrated into electrical grid. However, the introduction of a large number of PV generators could have a negative impact on electrical grids, such as polluting the grid, causing grid instability, and even resulting in the voltage collapse if the relevant stability and control issues are not properly considered. For solar power generation systems, the conventional methods,such as Maximum Power Point Tracking (MPPT) method, only provide individual power output depending on solar lighting condition. The power output is not stable and will disturb the electric gird. This will result in the imbalance of the power supply and demand of the whole distributed power generation region and result in oscillation.

Connecting solar PV generators to electrical grid is normally distributed. Solar PV grid-connected power generation systems therefore can be formed as a distributed system. They are often designed to work independently. This can save investment, reduce energy consumption and improve the reliability and flexibility for integrating solar power into electrical grid. There are three kinds of control modes to control distributed solar PV grid-connected power generation systems: the centralized control, the decentralized control and the distributed control [6],[7],[8],[15]. The centralized control is to send control commands to all the PV generators by a central controller. If the number of PV generators is large, then collection information and control will be quite expensive [20]. In the decentralized control, the information each PV generator used is from its local measurement without communication among PV generators. So the number of PV generators can be large. However, if the power demand or the maximum power generation capacity of a PV generator changes suddenly, this control scheme will have no capability to regulate their outputs to meet power demand. The distributed control is to employ the local network to exchange information among neighboring PV generators and use its local information and neighboring information to implement the control. It combines the advantages of the centralized control and the decentralized control without their flaws. Therefore most large-scale solar PV grid connected power generation systems adopt the distributed control scheme.

The traditional control methods of DG systems include constant power (PQ) control, droop control, and constant voltage and frequency (V/f) control. Due to the randomness of PV output power, droop control and V/f control are not suitable for PV power generation systems. PQ control is committed to make the output power of the plant reach the given reference. In [8], a self-organizing cooperative control method has been proposed to make a group of PV generators converge and operate at the same ratio of available power. A center-free control strategy has been developed to make all the PVs have the same reserve ratio with respect to their maximum available power and to make their aggregated output support power network by providing power regulation service within the power limit. There is cooperative control which is responsible for coordinating the power output and allocating them to execute the lower level implements the model predictive control. [10],[11],[16],[18] Model predictive control is a very effective control method because it controls systems according to the predictive values of the control variables in the next period of time. An dynamic matrix control (DMC) based model predictive control scheme is adopted in this paper. The merit of DMC lies in taking object's step response which is easy to obtain by measurement from model. Thus it is unnecessary to get the accurate mathematical models for large-scale PV power generation systems. Under this control strategy, all the PV generators in a distributed PV power generation system will work cooperatively, and the performance of the whole system will be better than the performance when they work independently.

The rest of this paper is organized as follows. The structure and modeling of a distributed PV power generation system is presented in Section I. A cooperative model predictive control strategy for distributed PV power generation systems is proposed in Section II. Simulations conducted on a standard 14-bus distribution power generation system are shown in section III. The conclusion is drawn in Section IV.

I. DISTRIBUTED PV POWER GENERATION SYSTEMS

In a distribution network with many PV generators, its operating condition needs to be adjusted due to many varying factors, such as load and sunlight fluctuations. As was pointed out in the introduction, it would be impossible to determine and maintain a feasible operating condition if all of the PV generators are independently run under the decentralized control configuration shown in Fig. 1(a). The centralized control mode shown in Fig. 1(b) is neither practical nor reliable since it requires global collection and exchange of information. To handle numerous PV generators in the network, we propose to implement the distributed control configuration as shown in Fig. 1(c).

Once the power output of each group is dispatched, the proposed cooperative control coordinates all the outputs of PV generators in the same group so that, even though the output capacity of individual PVs may have large swings, a given profile is achieved for their utilization and the sum of their outputs converges to the dispatched value. The local information sharing within one group of PVs may be intermittent, asynchronous, and of varying topology.

The utilization profile for PVs in the group can be determined according to such considerations as economic and regulatory policies. In what follows, the proposed distributed cooperative control is designed for the case of the fair utilization profile, that is, that all of the PVs in a designated group are to be run at the same active and reactive power output ratios.

Modelling a Single-Phase PV Power Generation System

According to the PV module equivalent circuit in the Fig.2 we can model the simulation model of PV.

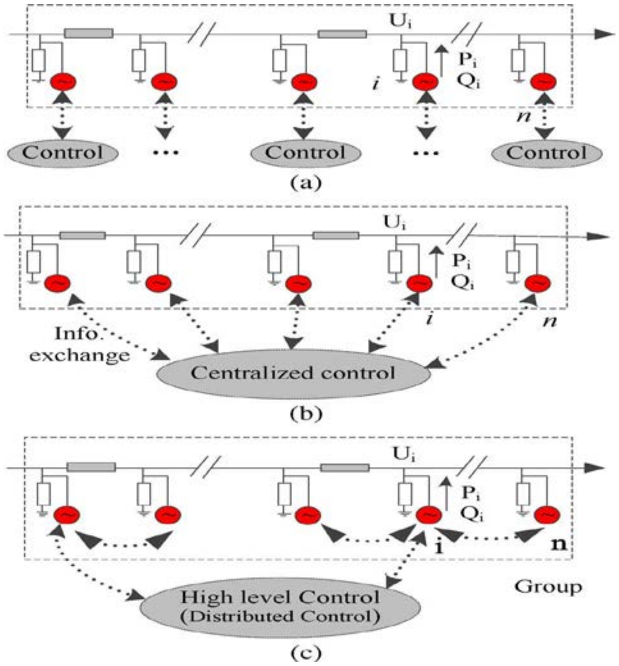

Fig.1 Distribution Network systems

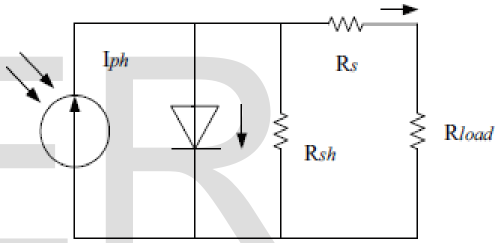

Fig. 2 PV module equivalent circuit

According to the PV module equivalent circuit in the Fig. 2, we can model the simulation model of PV module. And we can obtain the output current of the PV unit as following:

$$\mathrm{Ios}=\frac{\mathrm{Iph}}{\exp\left[\frac{q\,(V+\mathrm{IRs}\,)}{\mathrm{AkT}}\right]-1} \qquad (3)$$

A simplified diagram for a single-phase PV grid-connected system is shown in Fig. 3, where Vd represents the output voltage of the PV arrays; vc is the voltage across the capacitor C; vg is the voltage of the grid; il and ic are the currents flowing through the inductor and the capacitor of LC filter, respectively; ig is the output current of the PV generator and the current flown into the grid. In Fig. 3, a power diode is installed in the input terminal of the inverter to prevent power feeding back to the solar plate from grid. Four IGBTs form a bridge of two arms to realize DC/AC conversion. The inductor Ll and the capacitor C consist of a LC filter, Rl and Rc are damping resistors, Lg and Rg constitute the grid impedance.

According to the Kirchhoff's voltage law (KVL), the voltage equation is obtained from the right loop circuit of Fig. 3,

$$Vc + icRc = igRg + ULg + vg \qquad (4)$$

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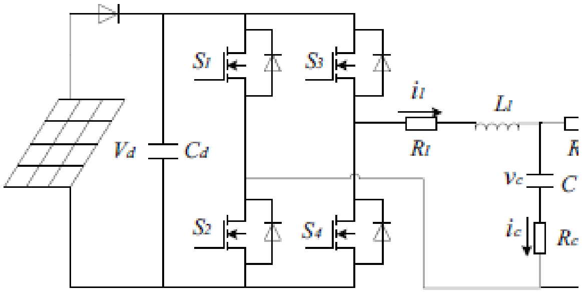

Fig. 3: Single-phase PV grid-connected

According to the Kirchhoff's voltage law (KVL), the voltage equation is obtained from the right loop circuit of Fig. 3,

$$Vc + icRc = igRg + ULg + vg \quad (4)$$

Then according to the Kirchhoff's current law (KCL), the current equation is obtained from the node among Ll,C and Rg,

$$Il = ic + ig \quad (5)$$

Where

$$Ic=C\frac{dvc}{dt}, ULg = L\frac{dig}{dt}. \quad (6)$$

By selecting the current of the grid ig and the voltage of the filter capacitor vc to constitute vector x = [ig; vc]T as the state variable, the voltage of the grid vg as the disturbance variable w, the current of the inductor il as the input variable u of the system, and ig as the output variable y of the system, therefore, the state-space model of the single-phase PV grid-connected power generation system is obtained. The state equation is described as:

$$\dot{x} = Ax + B1u + B2w \quad (7)$$

And the output equation is described as:

$$y = C1x + D1U + D2w \quad (8)$$

where

$$A = \begin{bmatrix} -Rc + Rg/Lg & 1/Lg \\ -1/C & 0 \end{bmatrix}$$

$$B_1 = \begin{matrix} -1/Lg \\ 0 \end{matrix}, \quad B_2 = \begin{matrix} Rc/Lg \\ 1/C \end{matrix}$$

$$C_1 = [\,1\ \ 0\,], D_1 = [\,0\,], D_2 = [\,0\,]$$

II. COOPERATIVE MODEL PREDICTIVE CONTROL

A distributed control scheme based on the fair utilization profile has been proposed to ensure the energy balance of the system[8], [11]. For easy control of power output, we adopt the same power output ratio for each PV generator. Since solar power output is changeable due to time-varying light condition, it is hard to control the whole distributed power generation system if we use the different power output ratio. Its aim is to make all the PV generators work at the same power output ratio,

$$\frac{P1}{P1max} = \cdots = \frac{Pi}{Pimax} = \cdots = \frac{Pn}{Pnmax} = \alpha \quad (9)$$

where Pi and Pimax are the instantaneous power output and maximum power output of the ith PV generator, respectively ;α is the given power output ratio.

According to (9), the ratio is the utilization percentages of all the PV generators and they are required to be the same at the steady state. In the following, a two-level control strategy is proposed. The upper level is cooperative control and the lower level is model predictive control based on dynamic matrix control (DMC). The task of the upper level cooperative control is to dispatch the output power. The lower level model predictive control is to control the PV generator to dynamically follow the given power output. Now we design the model predictive controller based on dynamic matrix control (DMC) for local PV generator. The advantage is that its algorithm has little computation and strong robustness.

III. SIMULATION RESULTS

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In this section, the standard 14-bus distribution power generation network is utilized to conduct the simulation based on MATLAB to verify the effectiveness of the proposed control strategy. The topology of the distribution network is shown in Fig. 5.

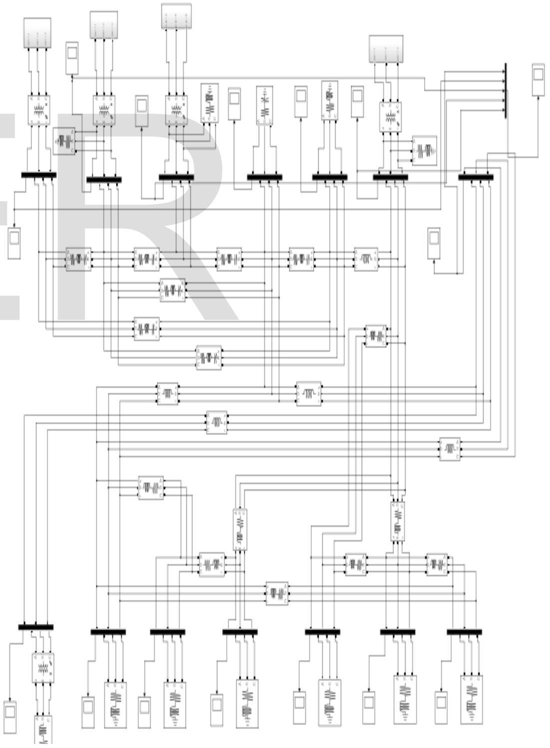

Fig.5 14-Bus system Network

Its distributed PV grid-connected power generation system includes 4 PV generators. Its main voltage is 13.8 kV in the network. The network parameters in Fig. 5 are:

Frequency: The fundamental frequency in the whole system is set as 50 Hz. The carrier frequency is 5 KHz, and the sampling frequency is 7 KHz.

Grid interface impedance:Rg = 0:2Ω and Lg = 0:45mH._ section line: The resistance, inductance and capacitance per kilometer are 0.01273 Ω, 0.9337 mH and 12.74nF, respectively. The length of each line is 10 km. In order to demonstrate the effectiveness and applicability of the DMC-based cooperative model predictive control strategy, two simulations for the distributed PV grid-connected power generation system with four PV generators are conducted in this paper. One is the DMC-based model predictive control with cooperative control. The other is the DMC-based model predictive control without cooperative control. For comparison purposes, the parameters in these two simulations are set to be identical.

Fig. 6 shows the dynamic responses of voltage of first PV generator buses. Fig. 6 (a) shows the dynamic responses of voltage of first PV generator without cooperative control. Fig. 6 (b) shows the dynamic responses of voltage of first PV generator with cooperative control.

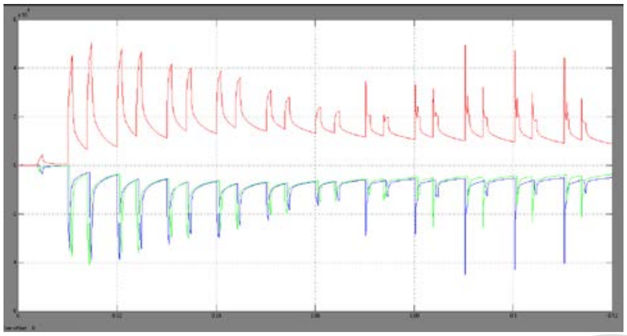

Fig.6 (a) Output at Bus1 without using MPC

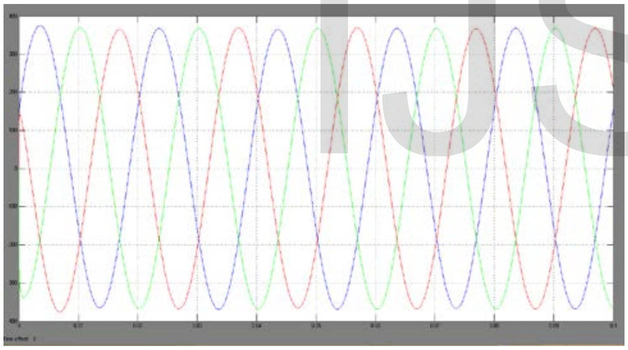

Fig.6 (b) Output at Bus1 using MPC

Fig. 7 shows the dynamic responses of voltages of four PV generators at the corresponding PV generators' buses. Fig. 7 (a) shows the dynamic responses of voltages of four PV generators without cooperative control. Fig. 7 (b) shows the dynamic responses of voltages of four PV generators with cooperative control. Obviously, the control strategy with cooperative control ensures that the voltage of every generator quickly converges to the steady-state value and has good dynamic property. The control performances with cooperative control out performs those without cooperative control. In this paper, we only provide a simple and easy control method for small-scale PV systems, which is not the best method. Due to fluctuation of the PV power generation system, the dynamic response of grid voltage has a high overshooting. But in the steady-state, the grid voltage converges to 1.0 pu.

The algorithm of the model predictive controller based on DMC are described as follows[21]:

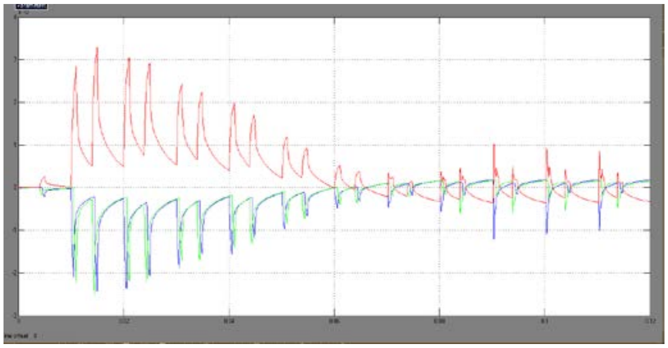

Fig.7 (a) Output at Bus7 without using MPC showing only the Final output. .(Load Bus)

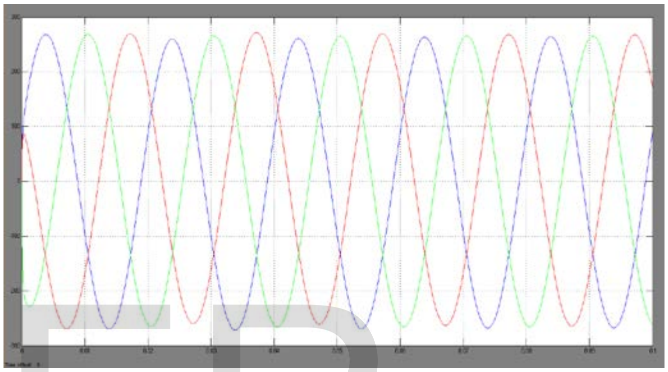

Fig.7 (b) Output at Bus7 using MPC showing only the Final output.(Load Bus)

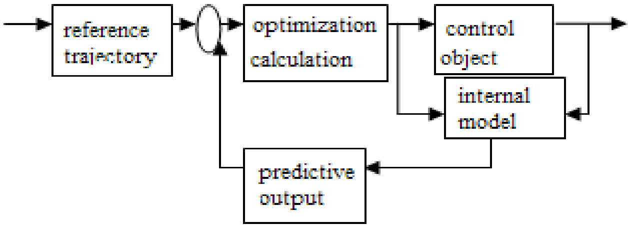

Fig.4 Dynamic Matrix Control Principle Design.

Taking step response as an object model: We first take the step as a control object model:

$$\hat{Y}_{PM}(k+1) = \hat{Y}_{P0}(k+1) + A_1 \Delta U_M(k), \qquad (10)$$

where ˆ YPM(k + 1) is the future predictive output with the control of ΔUM(k) at the moment t = (k + 1)T, ˆ YP0(k +1) is the future predictive output vector without the control of ΔUM(k), ΔUM(k) is the control increment vector. N is the length of time domain model; P is the length of time domain optimization; and M is the length of time domain control. N, P and M must satisfy the condition M ≤ P ≤ N. A1 is known as the dynamic matrix. It is constituted by the dynamic coefficient a1; a2; · · · ;

aN which can be obtained from generator step response. A1 can be written as:

$$\begin{bmatrix} a1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ aP & \cdots & aP-M+1 \end{bmatrix}_{PxM}$$

2) Feedback correction:
where y(k) and ˆypm(k) are the actual output and the predictive output at the moment t = kT, respectively; e(k) denotes the output error at the moment t = kT, ˆ YPc(k+1) is the predictive output vector after feedback correction, h is the correction coefficient vector.
3) The performance index of rolling optimization: DMC also has the rolling optimization part. Its optimization performance is expressed as follows:
minJ(k) = ||Yr(k) – YPc (k)||Q2+||ΔUM(k)||R2, (12)
where Yr(k) is setpoint vector, Q and R are known as the error weighting matrix and the control weighting matrix, respectively .
4) Reference trajectory: In predictive control, sometimes the output do not directly need to follow the required setting value, it only need to follow the following characteristics:
Yr(k+i)=βyr(k)+(1-β)ys(k), (13)
where ys(k) is the target setting value, yr(k) is the reference trajectory, the value of β is between 0 and 1, the bigger the value of β is, the smoother the process is.

CONCLUSION

A distributed two-level cooperative model predictive control scheme has been proposed for the power output regulation in a distributed system with a group of PV generators. The upper level cooperative control ensures all PV generators to work at the same power output ratio. The DMC based model predictive control guarantees that all PV generators can quickly and accurately track the reference signals .The simulations have been conducted to verify the validness and the effectiveness of the proposed control strategy.

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