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Abstract— **Random fluctuation of PV power is becoming a more and more serious problem affecting the power quality and stability of grid as the PV penetration keeps increasing recent years. Aiming at this problem, this paper proposed a control strategy of energy storage system based on Model Predictive Control (MPC). By the continuous optimizing of MPC, we can obtain the system parameters accurately, and then calculate the energy storage power. At the same time, this control took state of charge (SOC) and other parameters into account to ensure the health and stability of the energy storage units. Finally, simulation results proved the proposed control strategy had good performance and robustness.**

Keywords— *engrgy storage; power fluctuation; power quality; model predictive cotnrol;*

I. INTRODUCTION

In recent years, more and more grid-connected photovoltaic systems are being in operation around the world. As a result, the fluctuation and randomness of photovoltaic power is an important factor affecting the power quality of grid [1]. As the maximum power point tracking (MPPT) control is used in most of the PV systems, the output power necessarily varies with the change of illumination intensity and some other environmental factors [2]. In addition, the algorithm of the PV converter controllers and the parameters may also result in the variation of the output power [3]. This problem would be more serious when photovoltaic power systems access to low voltage distribution network, whose capacity is relatively small.

Many researches have proved application of energy storage units is an effective method to reduce the impact of PV power fluctuation. Obviously, the control strategy of energy storage systems is one of the most important aspects in related researches. In [4] a power management method for a hybrid system of PV and energy storage was proposed, which will keep power balance inside the a microgrid and keep the energy storage system always operating at a healthy state. Paper [5] examined aggregated and distributed connection topologies of the ESS technologies, and found the aggregated ESS could have a lower power rating due to smoothing effect in a wind farm. Paper [6] presented an energy manager for energy storage system in micro-grids. A battery lifetime model that uses the proposed Peukert lifetime energy throughput based on the workload of the battery is developed. The objectives of the energy manager are focused on improving the energy efficiency and extending the life expectancy of ESS while ensuring constraints of energy storage modules are complied with.

However, conventional control methods often use the data of past sampling periods, resulting in obvious delays in the output power of energy storage systems [7]. The delays will waste a large amount of energy of the storage units and increase the capacity requirements.

This paper proposed a control strategy of the energy storage system based on model predictive control (MPC). This control helps to maintain the power grid voltage stability and reduce voltage fluctuations when the PV system is working at the maximum power point. Another target of it is to avoid the energy storage units over charged or over discharged. MPC can provide a control command to the energy storage system without a delay by using prediction. This improvement can save a large part of the energy storage capacity. In this paper, the values predicted in the MPC are the grid impedance and other parameters. As a result, we can obtain the relatively accurate predictive value by rolling optimization, and the real value won't change over time. So this control strategy has better accuracy and robustness. Finally, simulation results proved the effectiveness and stability of the proposed control strategy.
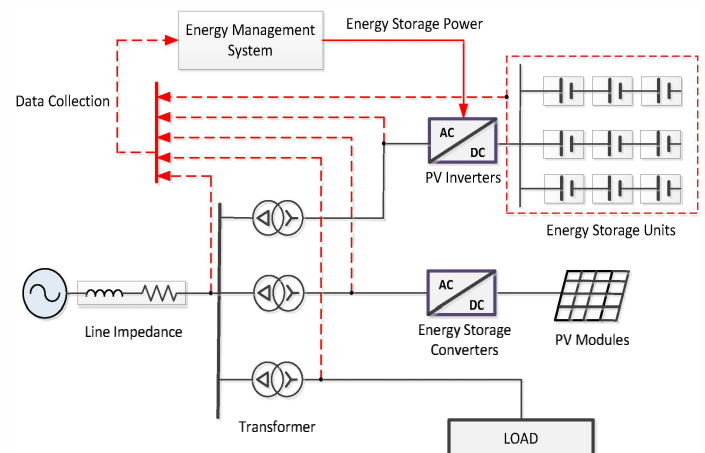

Fig.1 Hybrid system model of photovoltaic generator and energy storage units

II. System Model

The hybrid system of photovoltaic generator and energy storage units are shown in Fig.1. In this system, the maximum power of PV is 100kW and the capacity of energy storage is 200kWh. They are connected to a 380V three-phase AC bus, together with a local load. This hybrid system is regarded as a generating unit connected to the grid, and its total output power is expected to be smooth. By controlling the energy storage charging and discharging power, we can reduce the effect of PV power fluctuation and improve the power quality, such as voltage stability, at the point of common coupling (PCC).

In this system, the energy storage units are connected to the AC bus together with the PV. There are several advantages of this structure: firstly, we don't need to replace the PV inverters and transformers to larger ones. So we can install the energy storage system in a built PV system. Secondly, we don't need to stop the PV generators when repairing or replacing an energy storage unit. As we know, aging is a common problem of energy storage unit, such as battery. So this structure contributes to the stability of the hybrid system. Thirdly, this structure is less complex and easily controlled.
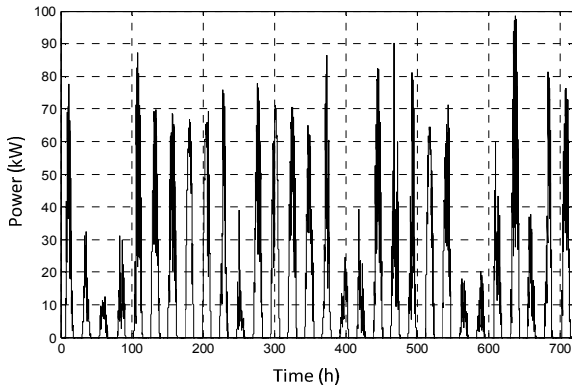

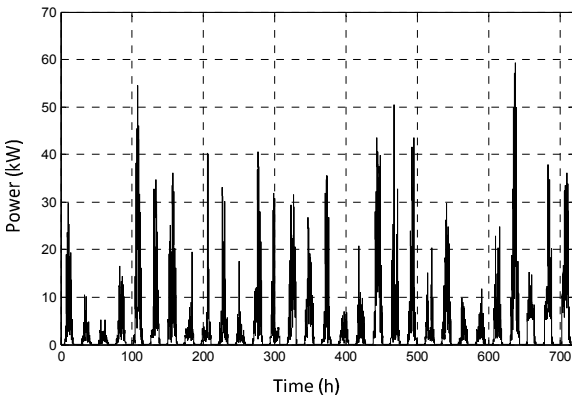Fig.2 30-days output power curve of a 100kWp PV system

Fig.3 10-minute largest change curve of 30-days PV power

We analyze the fluctuation characteristics of the PV output power. Change of environment is the main cause of fluctuation of PV output power. The fluctuation may affect the power quality of grid badly when natural factors change sharply [8]. Fig.2 shows a 30-days output power curve of a 100kWp PV system. To analyze its characteristics, we calculated the maximum power change of 10-minute horizon, as shown in Fig.3. We can see the maximum value of 10-minute largest power change is 59.5kW, accounting for nearly 60% of the nominal power of the PV system. In this situation, the voltage change would be pretty great, especially when the nominal power of a PV system is large or it connected into the low voltage distribution networks. In view of this situation, we proposed a novel control method based on MPC.

To solve the power fluctuation and power quality problems, we use large-capacity energy storage system to smooth the power and improve the power quality. The energy storage technology used in a distributed generation system should have following advantages: The energy storage units must have high degree of safety and stability. They should be guaranteed to work well without maintenance [9]. Secondly, the energy storage technology should have good economy, since the storage capacity is rather large to ensure long-term charging or discharging. Thirdly, the energy storage system should also be installed easily because many distributed generation systems are located in remote areas [10]. After considering the performance and characteristics of various conventional energy storage technologies, we choose batteries as the storage units in this paper. Recent years, energy storage batteries are widely used in power systems and renewable generation systems, owing to its technological maturity and economic advantage. So we should consider the operating characteristics when we are designing the control strategies.

III. Control Strategy of Energy Storage System

MPC is widely used in process control, as well have been used to control power converters and some switching power supplies [11]. MPC can make a great contribution to the accuracy and timeliness of the controlled system because it has the ability to predict the future change of the controlled system [12]. The overall process of MPC is consisted of three steps: predicting dynamic models of the controlled system, optimizing manipulated variables, and correcting dynamic models according to the collected data.

A. Optimization Cost Function

The target of the proposed model predictive control is to reduce voltage deviation caused by PV power changes, at the same time, try to avoid energy storage units over charged or over discharged. The optimization cost function is given by (1).

$$J = \min[\sum_{k=0}^{n_2-1} w_1 * (|SOC - SOC^*|) + \sum_{k=0}^{n_2-1} w_2 * \frac{1}{m_2}\sqrt{\sum_{i=k-m_2}^{k-1}(\frac{V(i)-V^*(i)}{V^*(i)})^2}] \quad (1)$$

Where w_1 and w_2 are the weight coefficients of the two parts of cost functions respectively. SOC is the state of charge of the energy storage system, whose ideal value is SOC^*. $V(j)$ is the measured voltage value of point of common coupling, and its ideal value is $V^*(j)$, the nominal voltage of the grid. n is the horizon width of rolling optimization in MPC strategy. m is the horizon width of calculating the voltage mean square value. This cost function confirms the control targets: smoothing the

PCC voltage to improve the power quality, and keeping the energy storage units working in a healthy condition. The coefficients w_1 and w_2 are determined by the fluctuation characteristics of the PV power and the capacity of the energy storage system. When the capacity of the storage system is rather large or the fluctuation of the PV power is not very dramatic, we can increase the proportion of w_2 to improve the smoothing result. Otherwise, we should increase the proportion of w1 to ensure the security and health of energy storage units.

The state of charge of the batteries is another important factor to influence the control effect and security. It is defined as the available capacity expressed as a percentage of the whole capacity of a battery. The SOC is calculated by

$$SOC(k + 1) = SOC(k) + \frac{[P_{bat}(k) + u(k + 1)] * \Delta t}{c} \quad (2)$$

Where P_{bat} is the energy storage power, Δt is the width of the sampling horizon, and C is the designed capacity of the energy storage system. In every control cycle, we predict the future SOC value with the calculated energy storage power.

B. *Constraint of the Control*

Another advantage of MPC is that the constraint conditions can be involved in the control process. In this paper, the SOC is not only used to calculate the cost function at every step, but also a constraint of the control. When we use batteries as energy storage units, we must ensure SOC of any battery does not exceed the range [0.2 1]. In addition, when we use the batteries as the energy storage units, the limitation of energy storage power should also be taken into account. Take lead acid battery for example, usually the maximum charge rate is 0.25C, and discharge rate is 0.5C. To summarize, the constraint function of this control is given by

$$-0.25P^* < [P_{bat}(k) + u(k + 1)] < 0.5P^* \quad (3)$$

$$0.2 \leq SOC(k) + \frac{[P_{bat}(k) + u(k + 1)] * \Delta t}{c} \leq 1 \quad (4)$$

C. *Model Expression*

Model prediction is necessary in energy storage power charge and discharge control, in this process, we need to predict the PV power, load power and energy storage power. Among them, The PV power can be obtained by short-term PV power forecasting.

The predicted load power is considered the same with the sampling value of the last horizon because it changes slowly. The energy storage power is the manipulated variable of the control. Above power values are predicted with errors inevitably, but the control strategy proposed in this paper is able to offset forecasting error partly by optimizing the model parameters. In other words, the predicted parameters of the system model may not be the same with the real ones, but they can make sure the output variable of the control will be the same with the sampling result.

At the same time, the health and service life are taken into account. Battery energy storage is widely used in microgrids and distributed generation systems. Therefore, we choose the batteries as the energy storage units in this paper. To avoid the batteries over charged or over discharged, the sampling SOC value is used as feedback to the energy storage power control.

Based on above analysis, the state variable and output variable can be calculated by (5) and (6).

$$x(k + 1) = x(k) + P_{bat}(k) + u(k + 1) + [P_{pvf}(k + 1) - P_{pv}(k)] \quad (5)$$

$$y(k + 1) = \frac{x(k + 1) - P_{load}(k)}{y(k)} * Z_L + U_0 \quad (6)$$

The manipulated variable u(k+1) is the change value of energy storage system power. x(k) is the total power of photovoltaic and energy storage. y(k) is the voltage of PCC. The rolling optimization can be completed by taking (5) and (6) into the cost function (1). P_{pvf}(k+1) is the predicted value of PV power, and P_{pv}(k) and P_{bat}(k) are the measured PV power and energy storage power respectively. Z_L is the grid impedance parameter, which is unknown and differs between different systems. When we obtain Z_L close to the real value, we can model the system accurately and this parameter won't change over time.
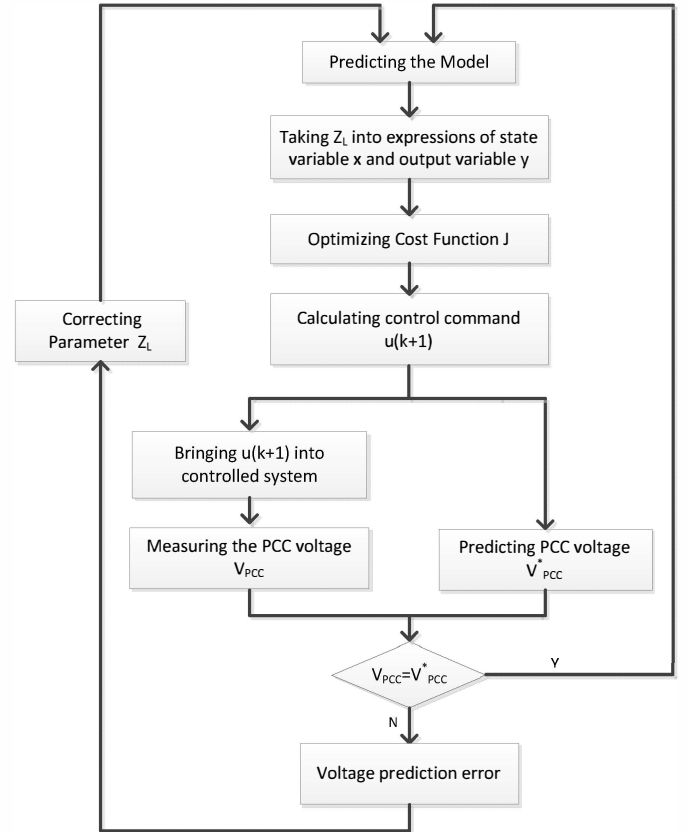

Fig.4 Flow chart of the proposed control

In this paper, the value of Z_L is corrected according to the error between the predicted and actual voltage of PCC. We calculate the predicted PCC voltage by (5) and (6), and then compare it with the sampling result at next control period to obtain the prediction error, which is used to correct the model. An accurate model of the hybrid system can guarantee the correctness of the control. The flow chart of this control strategy is shown in Fig.4.

IV. RESULT OF SIMULATION

In order to prove the proposed control algorithm is effective, simulations were carried out by MATLAB/Simulink. The data and parameters are gained from the actual PV system, whose structure is shown in Fig.1. The parameters of this hybrid system are listed in Table I. We use PV power data from an actual system in this simulation, which is shown in Fig.5. The power fluctuated greatly during this period of time.
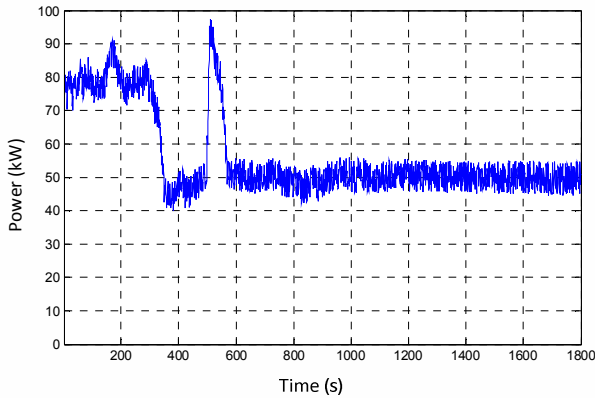

Fig.5 PV power curve of 1800s

TABLE I.   TABLE I. THE PARAMETERS OF THE SIMULATION

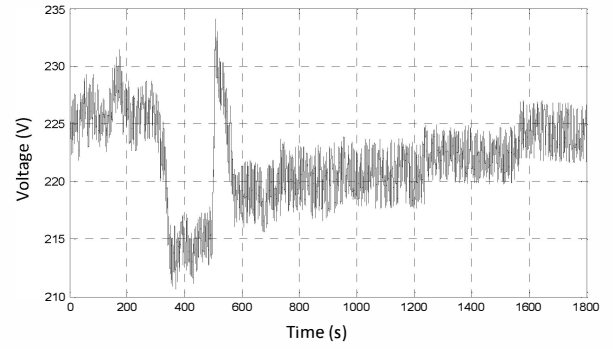| Parameters	symbol	value	unit
Nominal bus voltage	V^*	380	V
Nominal frequency	f^*	50	Hz
PV nominal power	P_{pv}	100	kW
The maximum load power	P_{load}	70	kW
Capacity of energy storage system	C^*	200	kWh
Line Resistance	R_{line}	0.15	Ω
Line Inductance	L_{line}	2	mH

Fig.6 PCC voltage curve before smoothed by energy storage system

A series of simulations were conducted on the PV data and parameters. Firstly, we did a simulation without the energy storage units, and the result is shown in Fig.6. In this situation, we can find voltage changed greatly because of the dramatic fluctuation of PV power, which will affect the power quality of the system.

When we control the battery energy storage system charging and discharging by the proposed control strategy, the PCC voltage curve and the voltage deviation curve during this period of time are shown in Fig.7. The PV power forecasting result used in this simulation had a lower accuracy than current advanced level, in order to proving the control method is still effective when the PV power forecasting is not accurate enough. The forecasting average error is 15%, and mean square error is 30%. The weight coefficients of cost functions w_1 and w_2 were 0.3 and 0.7 respectively. The ideal value of SOC is 0.8, which is large enough to make sure the batteries healthy and leave some room to charge when the PV power had a dramatic rise.
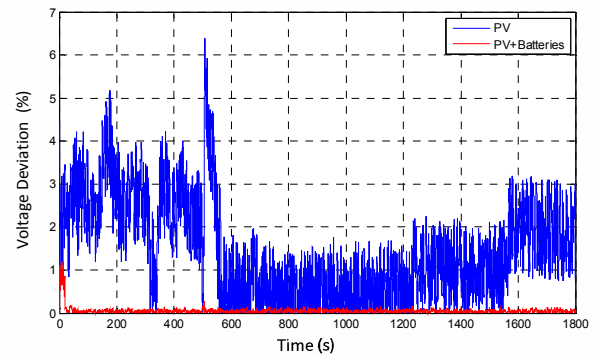

Fig.7 The voltage deviation curves before and after smoothed by energy storage system

We can find that the PCC voltage fluctuation can be smoothed effectively. This result shows that the continuous rolling optimization of the MPC helped improve the accuracy of the control over time. When the accurate model was obtained, the control result would be very good, and the influence of the photovoltaic power prediction error was reduced obviously. During the same period of time, the SOC curve of energy storage system is shown in Fig.8. We can find SOC was controlled in a reasonable range owing to the cost function and the constraint functions.
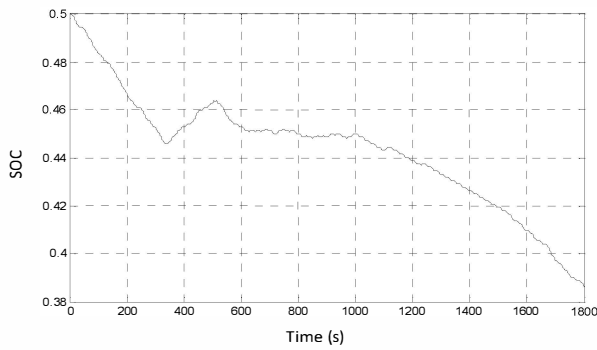
Fig.8 SOC curve of the MPC

At the same time, a series of simulations were carried out to compare the effect of MPC with the traditional Low Pass Filtering (LPF) method in controlling the energy storage in a PV system. The LPF algorithm now is widely used in controlling energy storage system to smooth the distributed generation output power. The simulation time and control step-size are both the same. The voltage deviation curves of these two control methods are shown in Fig.9, and the SOC curve of LPF method is shown in Fig.10. We can find, at this time, the SOC changed much greater than that of MPC, while the voltage deviation of LPF was also larger than MPC. If we increase the time coefficient of LPF to make the power smoother, the batteries would be over charged or over discharged. In other words, the proposed MPC method can improve the power quality more efficiently than traditional methods, owing to its ability of predicting the future events.
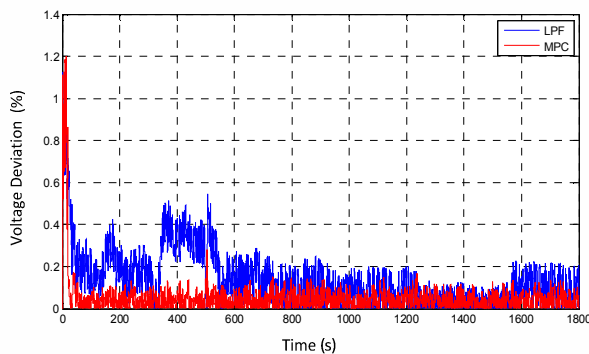

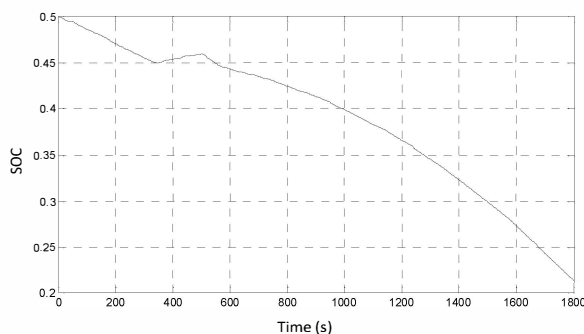Fig.9 Voltage deviation curves of LPF control and MPC

Fig.10 SOC curves of LPF control

We can also find a phenomenon: when the PV power had a dramatic fluctuation, the voltage curve of LPF control changed more sharply than that of MPC. So the robustness of MPC is better. For the MPC takes a period of time to finish the rolling optimization, the convergence of MPC will be obtained a bit slower than LPF control. But this process is pretty short, and the actual model will not change any more once the convergence is obtained. So this method has better robustness.

V. CONCLUSION

In this paper, we proposed a novel energy storage system control strategy based on MPC, aiming to smooth the power fluctuation and improve the power quality of a PV generation system. This control modeled the hybrid system accurately by continuous optimizing the line impedance and other parameters, and the model was used to calculate the charging or discharging power of energy storage units. The MPC had the ability to anticipate future events to avoid the delay of control. In the optimization process, the error of PV power forecasting As a result, the capacity of energy storage system was reduced, and the efficiency is higher. At the same time, the control took SOC and some other characteristics into account to ensure the health and security of the system. Simulation result proved the proposed control was effective to improve the power quality, and had better robustness compared to traditional method.

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