Model Predictive Control Based Power System Operation Planning of Grid Connected High Share Renewable Energy

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Model Predictive Control Based Operational Planning of a Power System with High Share Renewable Energy Resources

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Abstract—This paper presents operational planning scenarios of a power system with connected large-capacity renewable resources. The proposed operation technique is based on the Model Predictive Control (MPC). The operation plan works to solve large renewable penetration challenges via optimizing the outputs of the conventional and renewable power plants to overcome generation variability and uncertainty. The MPC has the ability to solve the optimization problem in predictive way to deal with both renewable energy and demand forecasting errors. The operation plan of the power system is studied during the four seasons in one year to cover different renewable resources circumstances. Simulation results are presented to verify the validity of the proposed technique.

Keywords—Power system operational planning, Renewable energy resources, Model predictive control.

I. INTRODUCTION

The new trend in recent power grids is increasingly depending on variable renewable energy resources (RES) as solar and wind powers. While RES penetration rises in the future grids, difficulties like handling the unpredictable output power becomes more challenging throughout the power system operation traditional technologies [1-3].

The future expansion in high share renewable energy leads to complex, variable and uncertain nature in demand and RES profiles. The resultant shape of this profile is hard to follow by the traditional dispatchable resources like thermal and hydro power units without specially designed techniques. An intelligent and predictive control approaches is recommended to follow RES high ramping of the new profile [1].

A day-ahead operation plan is used to dispatch the demand among the conventional and renewable resources. Whenever a variety of generation resources is available, different characteristics may help or restrict the optimal operation of the grid. In order to optimize the power system operation, dispatching techniques should take into consideration the forecasted RES output [4].

The operation optimization problem is constrained with certain restrictions and limits to operate each generation unit safely and securely maintains power system conditions. The power system characteristics like output limits and ramping capability should be considered for each generating unit. On the other hand, line capacity and voltage profile should be maintained within safe operation region [2-4].

Many researchers have presented methods for the commitment and dispatching issues via introducing different operation methods [5-9]. In [5], the authors formulate the optimization problem to design optimal dynamic energy management for smart grid taking into consideration the predicted demand and variable renewable sources. Single level control/optimization to cope with the challenges of RES uncertainty has been presented in [6-7]. Methods depending on power system flexibility measurement to securely dispatch and control both generation and storage units have been described in [8-9].

In this paper, the MPC is utilized to perform the operation plan. The MPC has the ability to calculate the optimal set-points of the generation units in current time sample, while considering the future forecasted RES profile samples. The proposed technique combines the optimization and control benefits to solve the objective function with minimum cost and safe operation. In addition, the predictive manner of optimization helps to reduce the forecast errors in the future time horizon. Compared to the previously discussed techniques, the proposed technique has the following key features: model dependent, predictive capability, flexible design and control, reference tracking, and ability to solve the problem with large number of degree of freedom [10]. The future power system operation planning is essential for both the grid operator and planner to study many scenarios of operation and avoid difficulties during real-time operation. In addition, it is decisive for the grid planner to estimate the grid needs for the new storage technologies and define its characteristics and modes of operations.

The remainder of the paper is arranged as follows. In section II, power system grid under study is presented. State-space modelling is introduced in section III. MPC based operation is designed in section IV. Simulation results are presented in section V. Finally, section VI summarizes the main conclusions.
II. POWER SYSTEM GRID UNDER STUDY

The proposed technique is applied on a power grid for the operation plan. The grid configuration is simplified to represent the grid model in single bus model as shown in Fig. 1. The plan for grid is to increase the renewable share in the future to 25% of total generation capacity (14GW for wind power and 11GW for solar share).

According to the plan for this case study, the generation expansion plans for thermal power plants as steam, gas and combined cycle power plants will represent 50% (50GW). Furthermore, a nuclear power plant and coal based plant are planned to be about 6.5% and 16%, respectively. In addition, the total share of hydropower is 2.8GW. The forecasted demand profile has a peak of 91GW and the total installed generation capacity will reach about 100GW. In order to get more flexible reserve power for peak-hours, a 2.1GW Pumped Hydro Storage (PHS) system and a 5GW market interconnection are intended for safe operation.

\[
x(k + 1) = Ax(k) + Bu(k) \\
y(k) = Cx(k) + Du(k)
\]

For each power generation unit in Fig. 1, the energy unit is represented by a state-space equation. It is modelled by an equation for the balance between the original source (infeed), output power and energy losses/curtailment. The following equations represent the state-space model for each unit type which is derived from state-space equation in (1).

\[
\begin{align*}
\text{PHS:} & \quad \dot{x}_{\text{PHS}} = -\frac{\eta_{\text{PHS}}^2}{C_{\text{PHS}}} p_{\text{PHS}}^\text{in} + \frac{\eta_{\text{PHS}}}{C_{\text{PHS}}} p_{\text{PHS}}^\text{out} & (2) \\
\text{Hydro:} & \quad 0 = \eta_h^{-1} p_h + p_{\text{cur},h} - d_h & (3) \\
\text{Thermal:} & \quad 0 = \eta_{\text{th}}^{-1} p_{\text{th}} - d_{\text{th}} & (4) \\
\text{Coal:} & \quad 0 = \eta_c^{-1} p_c - d_c & (5) \\
\text{Nuclear:} & \quad 0 = \eta_n^{-1} p_n - d_n & (6) \\
\text{Wind:} & \quad 0 = \eta_{\text{wind}}^{-1} p_w + p_{\text{cur},w} - d_w & (7) \\
\text{Solar:} & \quad 0 = \eta_s^{-1} p_s + p_{\text{cur},s} - d_s & (8) \\
\text{Load:} & \quad 0 = \eta_l p_L - P_{\text{Lshd}} - d_L & (9)
\end{align*}
\]

The Energy Storage system is modelled by the differential equation in (2). It is characterized by $C_{\text{PHS}}$, the storage capacity, $x_{\text{PHS}}$, the state charge of the battery. The charging and discharging power are $P_{\text{disCH,PHS}}$ and $P_{\text{disCH,PHS}}$, respectively. The parameters $\eta_{\text{th}}$, $d_{\text{th}}$ and $P_{\text{th}}$ are the efficiency, input fuel and output power from thermal units, respectively. The renewable energy parameters for wind and solar units are $d_{\text{w}}, \eta_{\text{w}}, P_{\text{w}}, P_{\text{w},\text{cur}}, P_{\text{w},\text{out}}$. The curtailed RES power are $P_{\text{cur,h}}, P_{\text{cur},w}$ and $P_{\text{cur},s}$. The demand model is expressed by $P_L$, $d_L$, and $\eta_L$, besides the load shedding power $P_{\text{Lshd}}$. The nuclear and coal generation have different characteristics when compared with conventional units and also restricted to hard constraints when it is compared to flexible thermal units. $P_{\text{th}}$ and $P_{\text{w}}$ are the nuclear and coal dispatched power with production efficiencies of $\eta_{\text{th}}$ and $\eta_c$.

For the interconnected network, the balancing power equation between generation and load is illustrated in (1), whereas, the interconnected lines of the power network are expressed in (11). The difference between injected (input) and absorbed (output) power at each bus $v$ is identified for the interconnection representation.

\[
P_{\text{dc,PHS}} - P_{\text{ch,PHS}} + P_h + P_{\text{th}} + P_{\text{w}} + P_{\text{out}} + P_{\text{Lshd}} = 0 \tag{10}
\]

\[
\sum_v p_{\text{in}}^v - \sum_v p_{\text{out}}^v = 0 \tag{11}
\]

The generation/load balancing equation has vital role to ensure the system security. The market interconnection with $L_{\text{in}}$ emerged in the balancing equation as a source/load upon the market operation scenario.
IV. MODEL PREDICTIVE CONTROL DESIGN AND IMPLEMENTATION

The main benefit of the MPC is the prediction horizon which is crucial for dealing with RES uncertainty and variability challenges. The main principle of MPC is to convert the control problem into optimization objective function and solve it during the prediction horizon according to certain constraints and limitations [10].

In this paper, the MPC MATLAB toolbox is used to design the MPC for power system operation. Figure 2 shows the MPC SIMULINK block diagram. At sample $k$, the predicted output $y$ of the plant model is compared with reference trend $r$ with the effect of a measured disturbance $d$. The quadratic optimizer is used to generate a manipulated input $u$ for the next sample $k+1$.

The state of charge reference trajectory is tracked by the MPC objective function by minimizing the error between it and the actual output state of charge. To represent the RES infeed profiles and load profiles, the forecasted profiles assigned at manipulated disturbance input for the MPC block. The calculated manipulated variables alongside with the infeed profiles are assigned to the state-space model of the power grid. The Simulink model provides the ability for system boundaries adaption in real-time. The MPC controller is designed to satisfy the objective function in (12). In order to achieve better performance, the prediction and control horizon are assumed to be $p = 10$, and $m = 1$, respectively. Those values ensure sufficient safety against disturbance profiles forecasting error.

$$
\min_{\Delta u} \left( \sum_{i=1}^{N} \omega_{y,i}(r_{i} - y_{i})^2 + \sum_{i=1}^{N} \omega_{u,i} \Delta P_{i}^2 \right) \tag{12}
$$

Subject to:

$$
x(k + 1) = Ax(k) + Bu(k), \text{[equations (2) – (11)]}
$$

$$
P_{\min} \leq P \leq P_{\max} \\
y_{\min} \leq y \leq y_{\max} \\
\Delta P_{\min} \leq \Delta P \leq \Delta P_{\max} \\
\Delta y_{\min} \leq \Delta y \leq \Delta y_{\max} \\
P_{dc} P_{ch} = 0
$$

The variance between the anticipated output $y_i$ and the reference $r_i$ is weighted by factors $\omega_{y,i}$. In addition, if the change in manipulated input $\Delta P_i$ is subjected to certain relative importance, it is weighted by a factor $\omega_{u,i}$. The weighting factors represent the energy unit MWh cost or defined as the degree of effect on certain variables. For safety purpose, the energy storage system is prevented to charge and discharge at the same time as assigned in (12). The PHS is set to one mode of operation (charge/discharge) according to the logic diagram shown in Fig. 3. If the minimum operating output power from thermal conventional generator plus RES infeed is greater than the demand infeed, the ESS boundaries is set to charge when applicable. On the other hand, if the summation is negative, PHS is set to discharge. Another rules should be taken into account, if the RES share is increased or extra storage units is installed increasingly.

![Fig. 2. Model predictive control SIMULINK block diagram for the operation plan](image)

![Fig. 3. Energy storage system charging/discharging rule.](image)
V. CASE STUDY SIMULATION RESULTS

The proposed technique is validated by applying the power system operation technique on the grid under study. The simulation is performed over one week period sample for each season in one year. The demand and RES profiles are estimated according to pre-stored historical data and another anticipated demand grows to address the closest profiles for one year. As soon as the grid state-space equations are converted to state-space model, the MPC uses it to generate the set points for all manipulated variables. The generation unit’s characteristics are fed to the MPC to define the unit’s boundaries and rate of change limits. For the winter season, a 7 day period power dispatching in MW is simulated as shown in Fig. 4 and Fig. 5.

The figure shows the power set points (a)-(f), Fig. 4(a) represents the set-points for hydro power plant. The hydro output power is almost constant over the week, but because of the low demand in winter, a hydropower curtailment is recorded at the end of third day.

In Fig. 4(b), the figure shows the conventional energy power share (thermal, coal and nuclear). For RES generation, solar and wind power shares are significantly utilized over the week with multiple small curtailments due to the low loading. Figure 4(e) illustrates the total demand values with no load shedding recording.

Finally, Fig. 4(f) shows the predicted market share via market interconnection line, while the positive values represent the anticipated required power and the negative values denote the available power to export. The rest of results show the usefulness of PHS for the grid operation process. Figure 5 shows discharging and charging power of the PHS unit in the upper axis, while the PHS state of charge is shown in the lower one.

For the spring season, the loading becomes greater. Figure 6 presents the manipulated power calculation according to the optimization function. It is noted that, no load shedding, no RES curtailment or spilled hydro power is documented. In addition, the conventional power plants are increased to cover the demand response. Moreover, the requirements for extra power are hidden via the interconnection with another market.
Coming to summer season, the weather becomes warmer and the demand becomes extremely larger. The loading surges to register 91GW as shown in Fig. 7. The grid not only uses all available power but also, a repeated load shedding is recorded during the peak-hour. In addition, 3GW is requested from the interconnection market to cover the power shortage. Similarly, Fig. 8 shows the simulation results at fall, which is more similar to spring season.

During this season, PHS is not utilized because there is no free power from RES to store. Fall case is slightly larger demand than spring with extra power from market; no load shedding is made in this case. According to the simulation results, it is recommended to increase the ESS capacity to use it in summer nights during peak hours. In addition, flexible small gas turbines based generators are recommended to follow the high ramping of the RES to support grid during large fluctuation.

VI. CONCLUSION

This paper introduces a power system operation plan technique to integrate large renewable energy share with minimum impact of the uncertainty and variability problems. Model predictive control technique is used to design the controller by solving it as an optimization problem. The proposed technique not only designed to minimize the cost but also, it keeps the system security by working in predictive manner. The technique is applied on a future energy combination as a case study. The results indicate that, the technique gives the ability to the grid operator and planner to test any operation scenario and understand the grid needs for the future grid plans.

Fig. 7. Power set points for one week in summer season.

Fig. 8. Power set points for one week in fall season.

REFERENCES


