Security-constrained line loss minimization in distribution systems with high penetration of renewable energy using UPFC

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Abstract Focused on the challenges raised by the large-scale integration of renewable energy resources and the urgent goal of energy saving, a novel control scheme for the unified power flow controller (UPFC) series converter is proposed to achieve line loss reduction and security enhancement in distribution systems with a high penetration of renewable energy. Firstly, the line loss minimum conditions of a general distribution system with loop configurations are deduced. Secondly, security constraints including the permissible voltage range, the line loading limits and the UPFC ratings are considered. System security enhancement with the least increase in line loss is tackled by solving a much reduced optimal power flow (OPF) problem. The computational task of the OPF problem is reduced by deducing the security-constrained line loss minimum conditions and removing the equality

constraints. Thirdly, a hybrid control scheme is proposed. Line loss minimization is achieved through a dynamic controller, while an OPF calculator is integrated to generate corrective action for the dynamic controller when the security constraints are violated. The validity of the proposed control strategies is verified in a modified IEEE 33 bus test system.

Keywords Line loss minimization, Security enhancement, Unified power flow controller (UPFC), Renewable energy

1 Introduction

With global warming issues drawing more and more public concern, efforts to achieve reductions in greenhouse gas emissions are made in various fields. As electrical energy supplies are one of the largest contributors to carbon dioxide (CO₂) emissions, power systems are expected to become more environment friendly. Improvements can be made in two ways.

- 1) Energy saving is a very efficient solution to reduce greenhouse gas emissions. The power loss in developed countries is not more than 10%, and it is around 20% in developing countries [1]. A large amount of the power loss occurs in distribution systems. Therefore, line loss minimization in distribution systems is critical to achieve energy saving.
- 2) Renewable energy resources such as wind and solar energy are much cleaner than fossil fuels. Replacing the conventional thermal power generation by increasing the power generation from renewable energy is also efficient in reducing CO₂ emissions. The penetration of renewable energy into distribution systems is expected to increase dramatically [2–4]. However,

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renewable energy resources such as wind and solar energy are characterized as variable and intermittent. Voltage violations and line overload issues in distribution systems integrated with high levels of renewable energy can be quite severe, if precautions are not taken [4, 5].

The challenges raised by the large-scale integration of renewable energy resources and the urgent goal of energy saving require multi-functioned operational control, including line loss reduction, voltage regulation and line overload relieving. As the most versatile flexible AC transmission systems (FACTS) device, and with a properly designed control scheme, a unified power flow controller (UPFC) is capable of achieving these operational goals simultaneously.

Focused on the control objectives of this paper, some valuable research has been done on real-time dynamic control strategies. In [6], line loss minimization is experimentally achieved by a UPFC in a laboratory prototype system. Voltage regulation issues are commonly studied and solved via control of shunt var compensators and filters [7, 8]. Control strategies to regulate the voltage magnitudes by series devices are studied in [5]. As suggested in [5], to achieve the same voltage regulation goal, the rating of a series regulation device can be much smaller than that of a shunt device. Hence this paper tackles voltage violation through the control of the series converter of the UPFC. In [9], line overloads are alleviated by a UPFC through an online interactive algorithm. Real-time dynamic control strategies can achieve fast and efficient control. However, the control is often single-goaled with the control objective fixed.

On the contrary, optimal power flow (OPF) based calculations are able to make the operation more optimized and flexible with multi-objectives considered and multi-parameters optimized. OPF algorithms have been used to seek comprehensive optimizations of line loss, voltage profile and power flow distribution using UPFC [10–13]. However, a big challenge of implementing OPF algorithms in real-time operation is the computational task, which is time consuming and generally hourly based [14]. Continuously changing renewable energy outputs and loads makes it very inconvenient to implement OPF algorithms in real-time operation.

To combine the advantages of the two approaches above, and to reduce the computational cost, a hybrid control scheme consisting of a dynamic controller and an OPF calculator is developed in this paper. Line loss minimization is achieved through the dynamic controller based on phasor measurement unit (PMU) measurements. The OPF calculator is to generate corrective action for the dynamic controller to alleviate voltage violations, line overloads and

UPFC overloads. The computational task of the OPF problem is much reduced by deducing the security-constrained line loss minimum conditions and introducing PMU measurements into the OPF calculations. Through state estimation techniques, full observability of the distribution system can be achieved with fewer PMUs installed [15, 16]. The accuracy requirement of the measurements for real-time control and protection can be satisfied by data processing and filtering [17]. Therefore, with the development and the implementation of PMUs, real-time optimization and control are becoming more achievable.

In order to develop the control scheme, the rest of the paper is organized as follows. Line loss minimum conditions are deduced in Section 2. In Section 3, based on the deduced constrained line loss minimum conditions, system security enhancement with minimum increase of line loss is tackled by solving a much reduced OPF problem. Procedures to solve the OPF problem using PMU measurements are also proposed. The control scheme is designed in Section 4 to integrate the OPF calculation results for enhancing system security with the dynamic controller for line loss minimization. The case study in Section 5 proves the validity of the proposed control strategies, and conclusions are made in Section 6.

2 Line loss minimum conditions

In distribution systems, radial configurations are often preferred by distribution operators as these configurations require simple protection schemes. On the other hand, loop distribution systems perform better in reducing power loss, improving voltage profile, and line loading balancing [4], which are more favorable for saving energy and integrating renewable energy resources. As a result, reconfiguring a radial distribution system into a loop one has received a lot of attention [18, 19]. More complicated configurations of distribution systems, such as secondary grid networks and spot networks, are suggested in [20] to provide reliable power supplies for critical loads, where more than one loop configuration is used.

A general distribution system with loop configurations is shown in Fig. 1, where renewable energy resources are integrated. The distribution system has a buses and b lines. The voltage of Bus m ($m = 1, 2, \dots, a$) is $\dot{V}_m$. For Line k ($k = 1, 2, \dots, b$), the line impedance is $\tilde{Z}_k = R_k + jX_k$ and the line current is $\dot{I}_k$. A UPFC is installed on Line 1 and the two ports of the series device are numbered Bus 1 and Bus 2. $\dot{I}_U$ denotes the current of the UPFC installed line. The voltage integrated by the UPFC series device is $\dot{V}_{se}$.

The substations are represented by voltage sources and the loads in the distribution system are represented by

Fig. 1 Configuration of the studied system

current sources. According to [20], distributed generators cannot actively regulate voltage. The renewable energy generations are represented by current sources. The current flowing into the UPFC shunt converter is very small, and thus is neglected for the sake of simplicity [6, 21]. Hence, the UPFC is simplified to a current source $\dot{I}_U$ in series with the UPFC installed line. After the power devices and the UPFC are substituted by current and voltage sources, the superposition theorem can be applied. Formulas in this paper are deduced with variables in p.u. form.

The current phasor in the UPFC installed line can be controlled at a reference value so that the designated power system parameters are regulated at their desired settings [21–23]. For the purpose of this paper, the control scheme developed is to provide the current reference of the UPFC installed line, controlled at which line loss minimization and system security enhancement can be achieved simultaneously.

Firstly, the relationship between the total line loss of the distribution system P_{loss} and $\dot{I}_U$ is derived. P_{loss} is calculated as:

$$P_{loss} = \sum_{k=1}^b R_k I_k^2 \quad (1)$$

where I_k is the magnitude of $\dot{I}_k$.

For Line k ($k = 1, 2, \dots, b$), the relationship between $\dot{I}_k$ and $\dot{I}_U$ can be obtained by applying the superposition theorem:

$$\dot{I}_k = \tilde{H}_k \dot{I}_U + \dot{I}_{s,k} \quad (2)$$

where $\dot{I}_{s,k}$ is the component of $\dot{I}_k$ produced by other current and voltage sources when the UPFC installed line is open; $\tilde{H}_k$ is the coefficient between $\dot{I}_k$ and $\dot{I}_U$ calculated by (3) using electrical network theories [24]; $\tilde{H}_k \dot{I}_U$ is the component of $\dot{I}_k$ produced by the current source in the UPFC installed line alone.

$$\tilde{H}_k = -E_k Y_b A^T Z_n A^T E_l^T \quad (3)$$

where A is the incidence matrix of the associated graph of the distribution system; Y_b is the branch-admittance matrix; Z_n is the inverse matrix of the node-admittance matrix; and $E_k = [E_{k1}, E_{k2}, \dots, E_{kb}]$ ($k = 1, 2, \dots, b$) are defined as:

$$E_{ki} = \begin{cases} 1 & i=k \\ 0 & i=1, 2, \dots, b; i \neq k \end{cases} \quad (4)$$

By analyzing the real and imaginary components separately ($\dot{I}_k = I_{kx} + jI_{ky}$, $\dot{I}_U = I_{Ux} + jI_{Uy}$, and $\tilde{H}_k = H_{kx} + jH_{ky}$), the partial differential equations of $\dot{I}_k$ with respect to $\dot{I}_U$ can be derived from (2):

$$\begin{cases} \partial I_{kx} = H_{kx} \partial I_{Ux} - H_{ky} \partial I_{Uy} \\ \partial I_{ky} = H_{ky} \partial I_{Ux} + H_{kx} \partial I_{Uy} \end{cases} \quad (5)$$

I_k is calculated as:

$$I_k = \sqrt{I_{kx}^2 + I_{ky}^2} \quad (6)$$

The partial derivatives of P_{loss} with respect to I_{Ux} and I_{Uy} , P_A and P_B , are obtained from (1), (5) and (6):

$$\begin{cases} P_A = \frac{\partial P_{loss}}{\partial I_{Ux}} = 2 \sum_{k=1}^b R_k (H_{kx} I_{kx} + H_{ky} I_{ky}) \\ P_B = \frac{\partial P_{loss}}{\partial I_{Uy}} = 2 \sum_{k=1}^b R_k (-H_{ky} I_{kx} + H_{kx} I_{ky}) \end{cases} \quad (7)$$

Further, it can be derived from (5) and (7) that:

$$\begin{cases} \frac{\partial P_A}{\partial I_{Ux}} = \frac{\partial P_B}{\partial I_{Uy}} = 2 \sum_{k=1}^b R_k H_k^2 \\ \frac{\partial P_A}{\partial I_{Uy}} = \frac{\partial P_B}{\partial I_{Ux}} = 0 \end{cases} \quad (8)$$

where H_k is the magnitude of $\tilde{H}_k$.

It can then be deduced from (7) and (8) that the line loss minimization of the distribution system is achieved if the following conditions are satisfied:

$$\begin{cases} P_A = 0 \\ P_B = 0 \end{cases} \quad (9)$$

Subscript 0 is used to denote the values of the corresponding variables at the line loss minimum operating point satisfying (9), e.g., $\dot{I}_{k0}$, $\dot{V}_{m0}$ and $\dot{I}_{U0} = I_{Ux0} + jI_{Uy0}$. Therefore the line loss minimum conditions can also be expressed as:

$$\begin{cases} I_{Ux} = I_{Ux0} \\ I_{Uy} = I_{Uy0} \end{cases} \quad (10)$$

The control strategy to realize (10) will be elaborated in Section 4.

3 Security enhancement

3.1 Security-constrained line loss minimum conditions

In distribution systems with a high penetration of renewable energy, besides the line loss minimization problem, voltage violations and line overloads due to the variation of the renewable energy generation also need to be taken care of. The line loss minimum conditions given in (9) have to be violated in case the security of the system is challenged. An optimal security enhancement strategy is investigated in this section, by which the security of the system is guaranteed with the least increase in line loss.

By considering a current deviation of the UPFC installed line from the line loss minimum operating point, $\dot{I}_U = \dot{I}_{U0} + \Delta \dot{I}_U$, it can be deduced from (8) that:

$$\begin{cases} P_A = 0 + \int_{I_{U0}}^{I_{U0} + \Delta I_{Ux}} R_{all} dI_{Ux} = R_{all} \Delta I_{Ux} \\ P_B = R_{all} \Delta I_{Uy} \end{cases} \quad (11)$$

where ΔI_{Ux} and ΔI_{Uy} are the real and imaginary components of $\Delta \dot{I}_U$ respectively; R_{all} is calculated as:

$$R_{all} = 2 \sum_{k=1}^b R_k H_k^2 \quad (12)$$

From (7) and (11), the increase of the total line loss from the line loss minimum operating point, ΔP_{loss} , is:

$$\begin{aligned} \Delta P_{loss} &= \int_0^{\Delta I_{Ux}} R_{all} \Delta I_{Ux} d\Delta I_{Ux} + \int_0^{\Delta I_{Uy}} R_{all} \Delta I_{Uy} d\Delta I_{Uy} \\ &= \frac{R_{all}}{2} \Delta I_U^2 \end{aligned} \quad (13)$$

where ΔI_U is the magnitude of $\Delta \dot{I}_U$.

As shown in (13), the security-constrained line loss minimization problem can be solved by finding the value of $\Delta \dot{I}_U$ of the minimum magnitude that satisfies the security constraints of the system, denoted by $\Delta \dot{I}_U^* = \Delta I_{Ux}^* + j \Delta I_{Uy}^*$. The security-constrained line loss minimum conditions are therefore given by:

$$\begin{cases} I_{Ux} = I_{Ux0} + \Delta I_{Ux}^* \\ I_{Uy} = I_{Uy0} + \Delta I_{Uy}^* \end{cases} \quad (14)$$

To determine the value of $\Delta \dot{I}_U^*$, security constraints such as the permissible voltage range, the line loading limits and the UPFC ratings have to be considered.

1) Permissible voltage range

For Bus m ($m = 1, 2, \dots, a$), the relationship between $\dot{V}_m$ and $\dot{I}_U$ can be obtained from electrical network theories:

$$\dot{V}_m = \tilde{G}_m \dot{I}_U + \dot{V}_{s,m} \quad (15)$$

where $\dot{V}_{s,m}$ is the component of $\dot{V}_m$ produced by other current and voltage sources when the UPFC installed line is open; $\tilde{G}_m$ is the coefficient between $\dot{V}_m$ and $\dot{I}_U$ calculated through electrical network theories as (16); $\tilde{G}_m \dot{I}_U$ is the component of $\dot{V}_m$ produced by the current source in the UPFC installed line alone.

$$\tilde{G}_m = Z_{m2} - Z_{m1} \quad (16)$$

where Z_{ij} ($i, j = 1, 2, \dots, a$) is the element in the i^{th} row and j^{th} column of matrix $\mathbf{Z}_n$.

From (15), the voltage constraints $\Delta \dot{I}_U$ has to satisfy are given by:

$$V_{m,\min} \leq |\dot{V}_m = \dot{V}_{m0} + \tilde{G}_m \Delta \dot{I}_U| \leq V_{m,\max} \quad (17)$$

where $V_{m,\min}$ and $V_{m,\max}$ are the lower and upper limits of the permissible voltage range for Bus m ($m = 1, 2, \dots, a$) respectively.

2) Line loading limits

Likewise, the line loading constraints $\Delta \dot{I}_U$ has to satisfy are deduced from (2):

$$|\dot{I}_k = \dot{I}_{k0} + \tilde{H}_k \Delta \dot{I}_U| \leq I_{k,\max} \quad (18)$$

where $I_{k,\max}$ is the loading limit for line k ($k = 1, 2, \dots, b$).

3) UPFC rating constraints

Based on $\dot{V}_m$ and $\dot{I}_k$, the operating parameters of the UPFC can be easily deduced as $\dot{V}_{se} = \dot{V}_1 - \dot{V}_2$, $\dot{I}_U = \dot{I}_1$, and the real power transferred between the series and shunt converters $P_{dc} = \text{real}(\dot{V}_{se} \bar{I}_U)$, where $\bar{I}_U$ is the conjugate current of $\dot{I}_U$. The UPFC rating constraints $\Delta \dot{I}_U$ has to satisfy are given by:

$$\begin{cases} |\dot{V}_{se}| \leq V_{se,\max} \\ |\dot{I}_U| \leq I_{U,\max} \\ |P_{dc}| \leq P_{dc,\max} \end{cases} \quad (19)$$

where $V_{se,\max}$, $I_{U,\max}$, $P_{dc,\max}$ are the nominal series injected voltage, the rated current of the series converter, and the rated real power transferred between the series and shunt converters respectively.

With the objective and the constraints identified, the security-constrained line loss minimization problem can be translated to an OPF problem, by which the value of $\Delta \dot{I}_U^*$ can be determined. The objective function is given by (20), which subjects to the voltage constraints given by (17), the line loading constraints given by (18) and UPFC rating constraints given by (19).

$$\min |\Delta \dot{I}_U| \quad (20)$$

Instead of calculating system parameters by the power flow equations, the proposed OPF calculation uses a selected operating point (the line loss minimum operating point) to express the inequality constraints. Methods to obtain the operating parameters at the selected operating point ($\dot{I}_{k0}$ and $\dot{V}_{m0}$) based on PMU measurements are developed in the next subsection.

3.2 Procedures to solve OPF problem

The following procedures are used to solve the OPF problem in this paper, and the flowchart of these procedures are generalized in Fig. 2.

Step 1 Initialization. PMU measurements and constraints are obtained.

Step 2 Pre-processing. $\dot{I}_{k0}$ and $\dot{V}_{m0}$ are calculated. $\dot{I}_{k0}$ and $\dot{V}_{m0}$ can be calculated by voltage and current measurements of $\dot{V}_s$ and $\dot{I}_k$:

$$\dot{I}_{k0} = \dot{I}_k - \tilde{H}_k \Delta \dot{I}_U \quad (21)$$

$$\dot{V}_{m0} = \dot{V}_s - \sum_{k=1, k \in A_m}^b \tilde{Z}_k (\dot{I}_k - \tilde{H}_k \Delta \dot{I}_U) Sgn_{km} \quad (22)$$

where $\dot{V}_s$ is the voltage of the substation (assumed to be constant during the security enhancement process); A_m is the set of a path of lines from the substation to Bus m ; if $\dot{I}_k$ is in the same direction as path A_m , $Sgn_{km} = 1$, and $Sgn_{km} = -1$ if not; as shown in (11), $\Delta \dot{I}_U$ can be calculated by (23). Therefore, the values of P_A and P_B

are also required, which can be obtained by (7) from current measurements.

$$\Delta \dot{I}_U = \frac{P_A}{R_{all}} + j \frac{P_B}{R_{all}} \quad (23)$$

Step 3 OPF calculation. The OPF problem described by (17)–(20) is solved. Many OPF algorithms such as the genetic algorithm (GA) and the firefly algorithm (FF) have been proposed to solve OPF problems and to improve the calculation speed [13, 25]. However, the feasible region of the optimization variables is quite small and the involved constraints of the OPF problem are quite few. The OPF problem can be solved easily and quickly even by traversing through the feasible region. The feasible region is defined as:

$$\begin{cases} 0 \leq \Delta I_U \leq \Delta I_{U, \max} \\ 0 \leq \theta_U \leq 2\pi \end{cases} \quad (24)$$

where $\Delta I_{U, \max}$ is the upper limit of the feasible region and θ_U is the phase angle of $\Delta \dot{I}_U$.

Step 4 If a solution is found in the feasible region, output $\Delta \dot{I}_U^*$ and finish; if not, relax the system security constraints (17) and (18), and go back to *Step 3*.

The security-constrained line loss minimization problem is reduced to a much simplified OPF problem in the following ways.

- 1) The objective function is simplified by deriving the impact of a current deviation from the line loss minimum operating point.
- 2) The inequality constraints considered in the OPF calculations are expressed by the calculation results from PMU measurements. The equality constraints are removed.
- 3) The computational cost of the reduced OPF problem mainly depends on the number of the inequality constraints involved. The inequality constraints can be further simplified by removing the inequality constraints with no risk of being violated in operation or related to buses/lines remote from the UPFC.

It can be seen from 2) and 3) that, unlike the traditional OPF calculations incorporating the power flow equations, the computational cost of the reduced OPF calculations does not necessarily explode with the system scale. Thus the reduced OPF problem is more favorable for real-time optimization. As shown in the case study, a large OPF calculation delay is verified allowable for the proposed control scheme. Other optimizations could also be involved in the OPF calculations to achieve improvements in other aspects of the distribution system.

Fig. 2 Flowchart of the proposed procedures to solve OPF problem

4 Control scheme

Firstly, the dynamic controller for line loss minimization is developed. The schematic of the line loss minimization strategy is shown in Fig. 3a, where K_a and K_b are the gains of the two integrators; $I_{Ux,set} + jI_{Uy,set}$ is the current set value of the UPFC installed line in case the line loss minimization strategy is disabled; and $I_{Ux,ref} + jI_{Uy,ref}$ is the current reference value for the current control module of the UPFC series converter.

As shown in (8), P_A can be controlled to 0 through feedback integral control of I_{Ux} . Through the action of the integral controller, the steady state is reached when the error signal is zero, i.e., $P_A = 0$. Hence $I_{Ux} = I_{Ux0}$ is realized as shown in (11). Likewise, $I_{Uy} = I_{Uy0}$ can be realized by controlling P_B to 0. In this manner, the line loss minimum conditions are reached and the line current of the UPFC installed line is controlled at (10). In order to achieve line loss minimization and security enhancement simultaneously, the OPF calculation results are applied to generate corrective action to the dynamic controller for system security enhancement. The overall control scheme is shown in Fig. 3b. $\Delta I_{Ux}^* + j\Delta I_{Uy}^*$ is determined and generated by the OPF calculator. The steady state is reached when $P_A = R_{all}\Delta I_{Ux}^*$ and $P_B = R_{all}\Delta I_{Uy}^*$. In this manner, the line current of the UPFC installed line is controlled at (14) and thus security enhancement with least increase of the total line loss is achieved.

The hybrid control scheme combines the advantages of feedback dynamic control and OPF-based optimization.

(a) Schematic of the line loss minimization strategy

(b) Overall control scheme

Fig. 3 Control scheme of the proposed security-constrained loss line minimization

The total line loss is reduced quickly and efficiently through the dynamic controller, by which the optimization task of the OPF calculation is shared and greatly reduced. Corrective signals for the dynamic controller are generated by the OPF calculator to guarantee the security of the system. Through the proposed control scheme for security-constrained line loss minimization, comprehensive operational control is realized in distribution systems with high levels of renewable energy.

5 Case study

The validity of the proposed line loss minimization and security enhancement strategies is verified in a modified IEEE 33 bus test system, shown in Fig. 4. Three wind power generators (WPGs), WPG1, WPG2 and WPG3, are connected to the distribution system. A UPFC is installed at Bus 15 side of Line 14–15. The data of the lines and loads are presented in the Appendix A. The simulations are run in the power system simulator for engineering (PSS/E). The dynamic models and equipment ratings are also presented in the Appendix A.

The daily variation curve of the output power of all the three WPGs in p.u. is shown in Fig. 5. Without control of the UPFC, the total line loss of the distribution system, the minimum voltage of the AC buses and the maximum loading rate of the lines vary significantly under the natural power flow distribution, as shown in Fig. 6. The line loading rate is calculated as the magnitude of the line current divided by its loading limit. As shown in Fig. 6, operational characteristics of the distribution system are considerably influenced by the integration of the variable wind power generation, especially when the wind power generation is low. As fluctuation and intermittency are two inherent characteristics of renewable energy resources, the security and economic operation of the distribution system can be greatly challenged by the integration of high levels of renewable energy.

The proposed line loss minimization and security enhancement strategies are implemented to solve the above issues. Firstly, the time-domain control process of the

Fig. 4 Configuration of case-study system

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Fig. 5 Daily variation of wind power

proposed strategies is studied. The proposed line loss minimization strategy is implemented at 2.0 s (the output of the OPF calculator is 0) and the security enhancement strategy is implemented at 10.0 s (ΔI_U^* is generated by the OPF calculator to take corrective action). The total line loss of the distribution system, the voltage magnitudes of key AC buses at the receiving-end of the distribution system, and the line loading rates of heavily loaded lines are shown in Fig. 7.

In simulation, line current phasors of the lines and voltage phasors of the buses are monitored by PMUs to provide necessary measurements for the dynamic controller and the OPF calculator. The control parameters used are as follows: $K_A = K_B = 0.2$, $I_{Ux,set} + jI_{Uy,set}$ is given the value of the current phasor in Line 14–15 under the natural power flow distribution. $V_{m,min} = 0.95$ p.u., and $V_{m,max} = 1.05$ p.u. for all the AC buses. The line loading limits and the UPFC rating constraints are provided in the Appendix A. $\Delta I_{U,max} = 0.5$ p.u.. The calculated $R_{all} = 1.93$. The time-domain simulation is run when the wind power output is at its lowest level, 0.04 p.u..

As shown in Fig. 7, the total line loss of the distribution system is reduced from 154.2 to 140.4 kW after the line loss minimization strategy is implemented. The voltage profile and the power flow distribution of the system are also improved. However, the voltage magnitudes of Bus 17 and Bus 32 are still under 0.95 p.u. (the maximum permissible deviation from nominal system voltage is typically 5% [20]) and Line 1–2 is still overloaded. After the implementation of the security enhancement strategy, further improvements in the voltage profile and power flow distribution are made. The voltage magnitudes of Bus 17 and Bus 32 are raised above 0.95 p.u. and the loading rate of Line 1–2 is reduced below 1.0. However, the total line loss is increased only slightly, from 140.4 to 140.5 kW. Therefore, using the line loss minimization and security enhancement strategies together, security-constrained line loss minimization is achieved.

Under the operation conditions considered in the simulation process of Fig. 7, the simulated and calculated values of $\dot{V}_{m0}/\dot{I}_{k0}$ of the key buses and lines are compared in Table 2 in the Appendix A. The simulated values are those of $\dot{V}_m/\dot{I}_k$ at 9.9 s, when the line loss minimum operating point has been reached. The calculated values are obtained from (21) and (22) in the pre-processing step of the proposed OPF calculation procedures at 10.1 s, when the OPF calculator has been applied to take corrective action. As shown in Table 2, the calculated values of $\dot{V}_{m0}/\dot{I}_{k0}$ used in the OPF calculations are identical to the simulated ones. Operating parameters at the line loss minimum operating point can be obtained from the pre-processing step of the proposed OPF calculation procedures.

In Fig. 6, daily variation curves of the key parameters of the distribution system after the proposed strategies are implemented are compared with those under the natural power flow distribution. The loss incurred by the UPFC is considered in calculating the energy saved by the proposed strategies, which is assumed to be 1% of the value of the UPFC apparent power. The validity of the proposed scheme is verified under different wind power generation levels. As shown in Fig. 6, comprehensive operational optimization and control are realized for energy saving and security enhancement at all wind power generation levels. In this manner, the integration of higher levels of renewable energy can be achieved without compromising the security and economic operation of the distribution system. Besides, the ability to reduce the total line loss, regulate the bus voltages and relieve the line overloads intelligently alleviates the operational complexity of a distribution system.

The negative effects of the PMU measurement delay and the calculation delay of the OPF algorithm have also been studied. The time delay of the phasor obtained by a PMU is less than 40 ms on average [26]. A 0.3 s PMU measurement delay is assumed including the time consumed by data processing and filtering. The computing time for solving the OPF problem discussed in this paper is within 100 ms, even using a traversal algorithm. More severe time delays are assumed in the time-domain simulations. The responses of the total line loss and the voltage magnitude of Bus 32 to the change of the wind power are shown in Fig. 8. The power of the WPGs is reduced from 0.15 to 0.05 p.u. at 5.0 s. As shown in Fig. 8, the proposed control scheme is still valid with a 0.3 s PMU measurement delay and a 5.0 s OPF calculation delay. As the OPF calculator is only used to generate corrective action for the dynamic controller, a relatively long time delay of the OPF calculation could be tolerated. The feasibility of the proposed line loss minimization and security enhancement strategies in practical engineering is therefore confirmed.

Fig. 6 Daily variation curves of key parameters of distribution system

With the development of the modular multilevel converter based UPFC (MMC-UPFC), the equipment

(a) Total line loss of distribution system

(b) Voltage magnitude of key AC buses

(c) Line loading rate of heavily loaded lines

Fig. 7 Time-domain control process of the proposed line loss minimization strategy and security enhancement strategy

investment in the UPFC device is significantly reduced, e.g., the equipment investment in the Nanjing UPFC project is only 95 \$/kVA. For ratings of the UPFC considered in the case study, the equipment investment is about

Fig. 8 Responses of total line loss and voltage magnitude to change of wind power

\$11400. As shown in Fig. 6a, the amount of electrical energy saved is 254.4 kWh per day. Hence, the cost of the electrical energy saved is about \$135570 assuming that the cost of electrical energy is 73 \$/MWh and the effective life of the UPFC is 20 years. The economic benefit is significant, let alone the operational benefits produced by the system security enhancement.

6 Conclusion

In this paper, a novel control scheme for the UPFC series converter is proposed to achieve line loss reduction and security enhancement simultaneously in distribution systems with high levels of renewable energy. The control scheme is developed based on the deduced security-constrained line loss minimum conditions and the proposed procedures to solve the reduced OPF problem. The control scheme proposed in this paper sheds some light on how to combine OPF calculation results with a dynamic controller to realize fast and optimal control. An approach to reduce

the computational task of the OPF calculations by removing the equality constraints is also discussed.

With the proposed control scheme, the total line loss of the distribution system is maintained at the minimum value by the dynamic controller when no security constraint is violated. Otherwise, corrective signals are generated by the OPF calculator to guarantee the security of the system at the least increase in line loss. In this manner, comprehensive operational control is achieved for better integration of higher levels of renewable energy. The challenges raised by the large-scale integration of renewable energy resources and the urgent goal of energy saving are overcome. The validity of the proposed control scheme is verified in the case study.

The ability to reduce the total line loss, regulate the bus voltages and relieve the line overloads intelligently alleviates the operational complexity of a distribution system. The proposed control scheme can be incorporated into the construction of smart distribution systems.

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Appendix A

1) Line and load parameters

The data of lines and loads are given in Table A1, all expressed in p.u. (12.66 kV and 100 MVA based). In the case study, the load data given in Table A1 are used in all the time intervals of the day.

2) Dynamic models

- The main grid is equivalent to a synchronous generator modeled as constant internal voltage generator model (GENCLS). The power rating is 100 MVA, the inertia is 99 p.u. and the damping constant is 0.
- The renewable energy resources in the distribution system are modeled as a constant power source operated at a constant power factor [20] of 0.9. The power ratings of WPG1, WPG2 and WPG3 are 0.90 MVA, 0.54 MVA and 0.36 MVA respectively.
- Loads in the distribution system are modeled as constant power loads.
- The UPFC is modeled using the dynamic model given in [22]. The MVA rating of the UPFC is 60 kVA (the nominal series injected voltage is 0.48 kV, the rated current through the series converter is 72.2 A, and the rated real power transferred between the series and shunt converters is 40 kW). The equivalent resistor is

Table A1 Data of lines and loads

Sending bus	Receiving bus	Impedance	Loading limit (10^{-2})	Load at receiving bus (10^{-3})
0	1	$0.058 + j0.029$	4.5	$1.0 + j0.6$
1	2	$0.308 + j0.157$	2.6	$0.6 + j0.2$
2	3	$0.228 + j0.116$	2.4	$0.6 + j0.2$
3	4	$0.238 + j0.121$	2.2	$0.6 + j0.3$
4	5	$0.960 + j0.441$	2.0	$0.6 + j0.2$
5	6	$0.117 + j0.386$	2.0	$0.6 + j0.2$
6	7	$0.090 + j0.147$	2.0	$0.6 + j0.2$
7	8	$0.150 + j0.462$	1.8	$0.6 + j0.2$
8	9	$0.050 + j0.320$	1.6	$0.6 + j0.2$
9	10	$0.123 + j0.041$	1.5	$0.5 + j0.3$
10	11	$0.234 + j0.077$	1.5	$0.6 + j0.4$
11	12	$0.150 + j0.200$	2.0	$0.6 + j0.4$
12	13	$0.130 + j0.250$	2.1	$1.2 + j0.5$
13	14	$0.150 + j0.160$	2.0	$0.6 + j0.1$
14	15	$0.200 + j0.300$	1.8	$2.0 + j1.0$
15	16	$0.400 + j1.074$	1.9	$4.2 + j2.0$
16	17	$0.157 + j0.358$	1.5	$4.2 + j2.0$
1	18	$0.050 + j0.098$	2.4	$0.6 + j0.2$
18	19	$0.200 + j0.500$	2.3	$0.6 + j0.2$
19	20	$0.255 + j0.298$	2.5	$0.6 + j0.2$
20	21	$0.442 + j0.585$	2.0	$0.6 + j0.2$
2	22	$0.282 + j0.192$	1.5	$0.9 + j0.5$
22	23	$0.560 + j0.442$	1.5	$4.2 + j2.0$
23	24	$0.559 + j0.437$	1.3	$4.2 + j2.0$
5	25	$0.159 + j0.065$	2.1	$0.6 + j0.3$
25	26	$0.177 + j0.090$	2.0	$0.6 + j0.3$
26	27	$0.661 + j0.310$	1.6	$0.6 + j0.2$
27	28	$0.661 + j0.310$	1.8	$0.9 + j0.4$
28	29	$0.317 + j0.161$	1.5	$0.9 + j0.4$
29	30	$0.608 + j0.350$	1.5	$1.2 + j0.7$
30	31	$0.210 + j0.125$	1.6	$2.0 + j0.8$
31	32	$0.095 + j0.050$	1.2	$3.0 + j1.3$
32	17	$0.130 + j0.090$	1.8	–
21	11	$0.100 + j0.300$	2.1	–

Table A2 Simulated and calculated values of $\dot{V}_{m0}$ and $\dot{I}_{k0}$

Variables		Simulated value	Calculated value
$\dot{V}_{m0}$	Bus 14	$0.953 - j0.022$	$0.953 - j0.022$
	Bus 16	$0.951 - j0.005$	$0.951 - j0.005$
	Bus 17	$0.949 - j0.007$	$0.949 - j0.007$
	Bus 32	$0.949 - j0.007$	$0.949 - j0.007$
$\dot{I}_{k0} (10^{-2})$	Line 1–2	$2.491 - j0.796$	$2.491 - j0.796$
	Line 1–18	$1.591 - j1.055$	$1.591 - j1.055$
	Line 11–12	$1.615 - j0.751$	$1.615 - j0.751$
	Line 14–15	$1.366 - j0.646$	$1.366 - j0.646$

0.01 p.u. and the equivalent reactor is 0.2 p.u. The current controller PI gains K_{p1} and K_{I1} are 0.1 and 0.5 respectively. For the series converter, the reference current is produced by the proposed control scheme. For the shunt converter, the reference current is produced by DC voltage and reactive power controllers. The DC voltage regulation PI gains K_{p2} and K_{I2} are 2 and 10 respectively. The reactive power control PI gains K_{p3} and K_{I3} are 1 and 10 respectively.

3) Simulated and calculated values of $\dot{I}_{k0}$ and $\dot{V}_{m0}$

The simulated and calculated values of $\dot{V}_{m0}$ and $\dot{I}_{k0}$ of the key buses and lines are presented in Table A2, expressed in p.u. The angle of $\dot{V}_s$ is assumed to be 0.

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