Power system optimization by using combined Fast-Decoupled power flow algorithm and UPFC

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Electric power systems are structures that should operate stable in all scenarios. Unified power flow controller (UPFC), a flexible alternating current transmission system (FACTS) device, is one of the main assistants to achieve this necessity. In this study a control strategy for power flow optimization that based on the combined Fast-Decoupled (FD) method and UPFC is proposed. A detailed model was designed under MATLAB/Simulink platform in association with MATLAB editor. The IEEE-30 bus system was used to validate the model, and the results were addressed in terms of power loss values and optimization. According to the obtained results, it is observed that proposed model has ability to regulate system parameters for various conditions.

Keywords: *FACTS, Fast-Decoupled algorithm, Power system analysis, UPFC.*

1. Introduction

Losses in power systems are a significant source of inefficiency, particularly in the distribution and transmission phases. Researchers are carrying out diverse investigations to examine and mitigate these deficits. Accurately regulating the power flows in the transmission lines is one of the best ways to lower losses in the transmission stage. Technological developments help researchers in power system optimization studies [1], [2]. Loss reduction is greatly aided by the unified power flow controller (UPFC), which was created and is employed for this reason. Since its initial definition, researchers have employed UPFC in a number of investigations [3], [4]. A key tool in power system analysis, power flow analysis, often referred to as load flow analysis, is used to ascertain a power system's steady-state operating characteristics. Power flow analysis, also known as load flow analysis, is a crucial tool in power system analysis and is used to determine the steady-state operating conditions of a power system [5]–[8]. The Fast-Decoupled Method is a numerical technique commonly employed to solve power flow problems quickly and efficiently. The power system is represented as a network of buses (nodes), branches (lines and transformers), and loads, along with the generation at various buses. This involves creating an admittance or impedance matrix to represent the network's electrical characteristics [9], [10]. Buses in the power system are classified into three types. PV Buses (Voltage-Controlled Bus) have a specified voltage magnitude and are usually associated with generators that control their terminal voltage. PQ buses (load bus) have specified active and reactive power injections (real and reactive loads) and are typically associated with loads. Slack Bus (reference bus) is the reference buses with a specified voltage magnitude and phase angle. It is often the bus at the substation where the voltage is known accurately. An initial guess of voltage magnitudes and phase angles is required to start the iterative process. Often, flat start (equal voltage magnitudes at all buses) is used as the initial guess. The power flow equations are formulated in matrix form based on the network equations, including Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL) [11]–[13].

2. Fast-Decoupled Power Flow Analysis Method

One of the most popular numerical methods that frequently used to address power flow problems fast and effectively is the Fast-Decoupled Method. The Fast-Decoupled Method simplifies the power flow equations by decoupling the P and Q equations. This means that the real and reactive power equations are solved separately, making the calculations faster and more efficient.

The Fast-Decoupled Method uses an iterative process to converge to a solution. In each iteration, the voltage magnitude and phase angle at each bus are updated based on the decoupled equations. The process continues until the convergence criteria are met (e.g., voltage mismatches and power mismatches are within acceptable tolerances).

At PV buses, the voltage magnitude is a control variable, while at PQ buses, both voltage magnitude and phase angle are control variables. The slack bus maintains its specified voltage magnitude and phase angle throughout the iterations. Jacobian matrices are calculated to linearize the power flow equations. These matrices are used to update the voltage variables in each iteration.

The power flow solution is considered converged when the differences between successive iterations of voltage magnitudes and phase angles fall below a predefined tolerance level. Once the power flow analysis converges, the results include the voltage magnitude and phase angle at each bus, as well as real and reactive power flows in each branch. These results are essential for assessing the steady-state performance and operational limits of the power system.

Engineers can use the power flow results for various purposes, such as voltage profile analysis, contingency analysis, and determining system stability. The Fast-Decoupled Power Flow Method is favored for its computational efficiency while providing accurate results in most practical power system scenarios. However, it may not converge in certain cases, such as heavily stressed or highly nonlinear systems, and additional techniques or methods may be required [14]–[16].

The mathematical model for the power flow analysis using the Fast-Decoupled Method involves formulating a set of nonlinear algebraic equations that describe the steady-state behavior of a power system. The key equations are the real power balance equation (P) and the reactive power balance equation (Q) for each bus in the system. These equations are typically written in polar form using complex numbers.

For each PQ bus (load bus) and PV bus (voltage-controlled bus), the active and reactive power balancing equations can be expressed as given in (1) and (2) respectively:

$$P_i = \sum_{j=1}^{n} V_i V_j \left(G_{ij} \cos\left(\delta_i - \delta_j\right) + B_{ij} \sin\left(\delta_i - \delta_j\right)\right) \tag{1}$$

$$Q_i = \sum_{j=1}^{n} V_i V_j \left(G_{ij} \sin\left(\delta_i - \delta_j\right) + B_{ij} \cos\left(\delta_i - \delta_j\right)\right) \tag{2}$$

In these equations; *Pi* is the real power injection or consumption at bus *i*, *Qi* is the reactive power injection or consumption at bus *i*, *Vi* is the voltage magnitude at bus *i*, *δi* is the phase angle (in radians) of the voltage at bus *i*, *Gij* and *Bij* are the real and imaginary parts of the admittance *Yij* between buses *i* and *j*, *n* is the total number of buses in the system.

The goal of the Fast-Decoupled Power Flow Method is to solve this system of nonlinear equations iteratively until convergence is achieved. In each iteration, the voltage magnitudes and phase angles are updated based on the calculated power injections and the specified constraints.

The Jacobian matrices, which represent the sensitivity of power injections to voltage variables, are also used in the iteration process to linearize the equations and accelerate convergence.

The process continues until the voltage and power mismatches between iterations fall below a predefined tolerance level, indicating that a steady-state solution has been reached.

To solve the power flow problem using the Fast Decoupled Method, you make the following approximations:

1. Neglect the reactance (imaginary part of Y_{ij}) in the off-diagonal elements of the Y matrix, i.e., $B_{ij} \approx 0$ for all branches.
2. Assuming constant voltage magnitudes ($|V_i|$) for all buses.
3. Neglecting the voltage magnitude deviation from unity, $|V_i| \approx 1$ per unit.

With these simplifications, the real and reactive power balance equations can be decoupled, and you can iteratively solve them for voltage angles (δ_i) and voltage magnitudes ($|V_i|$). The solution process involves iterative calculations of δ_i and $|V_i|$ to achieve a balance of real and reactive power at each bus.

3. Details of proposed UPFC

General scheme of a UPFC which is located between two busbars is shown in Figure 1.

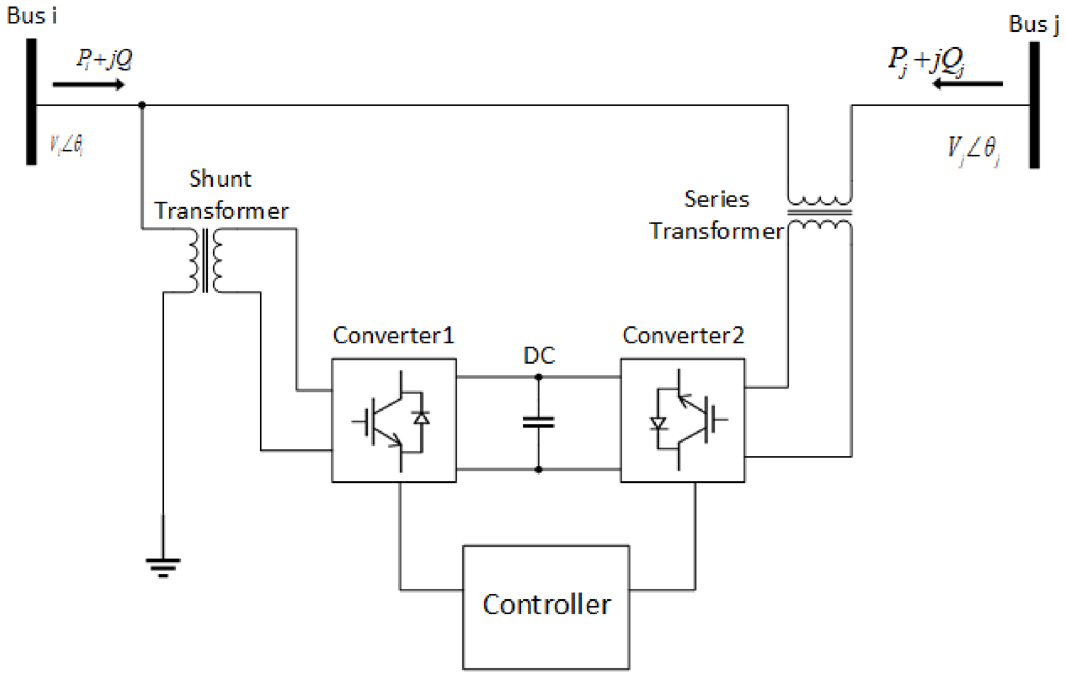

***Figure 1**. General structure of proposed UPFC.*

As shown in Figure 1, UPFC is modified by adding a controller unit according to the aim of study. This unit determines triggering angles and enables the controlling converters. Internal structure of proposed UPFC designed under MATLAB/Simulink platform is given in Figure 2.

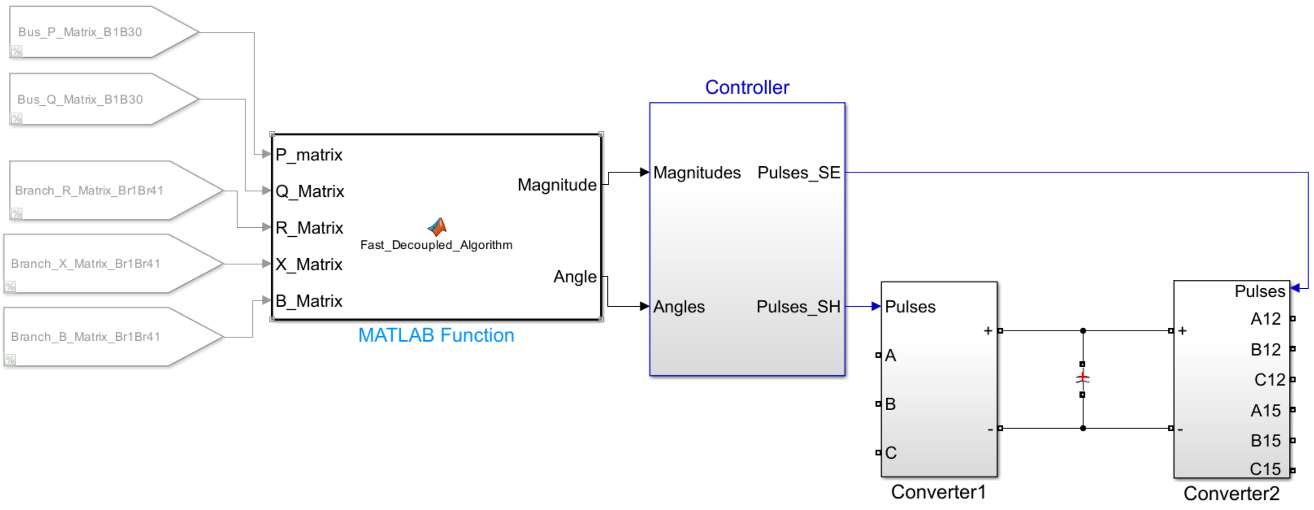

***Figure 2**. Designed UPFC.*

4. Experimental results and discussion

This study is focused on reducing transmission line losses by using a designed UPFC. In this context, it is aimed to optimize the line loadings. Method was validated by using IEEE-30 bus system. A line fault was supposed to occur on the line between buses 4-6. Designed system was simulated with and without fault conditions. This allows to have a reference for a better comparison. Results were summarized in Table 1.

Table 1. *Simulation Results.*

Between Buses	Line Loading without fault conditions (%)	Line Loading with fault conditions (%)	Line Loading with UPFC under fault (%)	Active Power Loss (MW) without UPFC	Active Power Loss (MW) with UPFC
1-2	126.7	144.4	125.1	6.02	5.21
1-3	63.7	48.4	54.9	2.39	2.7
2-4	64.6	23.4	41.3	0.3	0.66
2-5	60.8	73.8	59.4	3.61	2.9
4-6	***81***	***0***	***0***	***0***	***0***
4-12	71.5	103.9	76.2	0.0000	0.0000
6-7	29.1	16.8	25.2	0.23	0.32
6-9	44.5	29.3	35	0.0000	0.0000
12-15	56.6	81	58.8	0.31	0.22
12-16	47.2	103.3	77.4	0.12	0.07
16-17	23.7	81.8	67.1	0.03	0.02

Fast Decoupled method is more efficient computationally and widely used in power system analysis, especially for preliminary studies and operational planning. It provides a reasonably accurate solution for most practical power systems while significantly reducing the computational burden compared to the full Newton-Raphson method.

5. Conclusion

According to their dynamic behavior, electric power systems should be analyzed in detail for all types of operating conditions. As the power flow analysis is one of the most important approaches for this aim, this study proposes a UPFC device that assisted by fast decoupled power flow analysis algorithm. The IEEE-30 bus system is modelled under MATLAB/Simulink platform. Line fault condition was applied on designed system and system simulated for both without and with fault. Obtained results were discussed in terms of line loadings and active power losses. Results show that line loadings were balanced and active power losses were decreased by using proposed method.

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