Technical Paper

OPTIMAL SIZING AND ALLOCATION OF UNIFIED POWER FLOW CONTROLLER (UPFC) FOR ENHANCEMENT OF SAUDI ARABIAN INTERCONNECTED GRID USING GENETIC ALGORITHM (GA)

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Optimal Sizing and Allocation of Unified Power Flow Controller (UPFC) for Enhancement of Saudi Arabian Interconnected Grid using Genetic Algorithm (GA)

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***Abstract*–Flexible Alternating Current Transmission Systems (FACTS) are extensively used recently for improvement of large interconnected power systems performance in smart grids. Unified Power Flow Controller (UPFC) is the most versatile FACTS device which achieves a full-control of all of the transmission system parameters. UPFC is used with state-of-the-art control algorithms to optimize the dynamic performance of long-distance, bulk-power interconnection lines (bottlenecks). In this paper, the UPFC is investigated for a real 380 kV, 400 km, double-circuit tie transmission line connecting the central and western networks in the Kingdom of Saudi Arabia (KSA). Genetic Algorithm (GA) technique is used for optimal sizing and optimal allocation of the UPFC for the real system. Furthermore, the impacts of the presence of the UPFC on the existing protection system are assessed and feasible solutions are presented to overcome these challenges. MATLAB/SIMULINK is used to formulate the problem and to determine the optimum parameters and location of the UPFC. Simulation results are presented, discussed, and finally recommendations are given for an improvement of the interconnection system performance in terms of voltage profile and stability margin.**

***Index Terms*–Genetic Algorithm (GA) Optimization, Grid Interconnection, Flexible Alternating Current Transmission Systems (FACTS), MATLAB/SIMULINK, Smart Grid, Unified Power Flow Controller (UPFC)**

I. Introduction

IEEE defines the **F**lexible **A**lternating **C**urrent **T**ransmission **S**ystems, FACTS, as it is: "*a power electronic-based systems and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability*" [1]. FACTS are widely used for reactive power compensation in EHV/HV transmission systems and may be classified into different classifications. One classification is according to the connection of the FACTS device, either shunt or series FACTS. Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM) are examples of FACTS shunt compensation. Thyristor-Switched Series Capacitor (TSSC), Thyristor-Controlled Series Capacitor (TCSC), GTO Thyristor-Controlled Series Capacitor (GCSC), Thyristor-Switched Series Reactor (TSSR), and Thyristor-Controlled Series Reactor (TCSR) are examples of FACTS series compensation [2].

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On the other hand, FACTS may be classified according to the technology used in the switching devices into two main categories, Current Source Converter (CSC) and Voltage Source Converter (VSC). The former is also known as Line Commutated Converter (LCC) in which the switching devices can only be turned on (not off) and the turn off state is reached naturally by the line voltage commutation action. Thyristor valves are used in LCC technology since 1970s [3] in SVC applications. On the other hand, in VSCs, the switching devices can be turned on and off independent on the line voltage. VSCs use Gate Turn-off Thyristor (GTO) or Insulated-Gate Bipolar Transistor (IGBT).

Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC), and Hybrid Power Flow Controller (HPFC) are recent FACTS devices (not earlier than 1991) that consist of shunt and series VSCs as well [4], [5], and [6]. Recently, some efforts have been exerted in the literature for the optimal design and control of the UPFC in EHV and HV networks.

Despite the advantages of using UPFC within a system, it possesses significant challenges on the existing protection system reliability, especially for conventional distance relaying. As the UPFC is used to modify the line series impedance, terminal voltage, and line angle, it affects the distance relay reach (both magnitude and phase); hence, the distance relay is subject to either underreaching or overreaching [7], [8], [9], and [10].

In the following sections, a real case study for a series-compensated line project is presented and the distance relaying challenges associated with this series compensation are addressed. Then, another proposal using UPFC is studied and the feasibility of such choice is addressed. Accordingly, guidelines are presented for the optimization of the proposed solution using Genetic Algorithm (GA). Finally, a conclusion and future work recommendation are given for further enhancement of the current problems.

II. Unified Power Flow Controller (UPFC)

Unified Power Flow Controller (UPFC) is one of the most powerful and full-controllable devices among FACTS. UPFC provides a full-control of all of the basic power system parameters (transmission voltage, impedance, and phase angle). This facilitates a fully-decoupled control of active and reactive powers independently over the transmission line.

As shown Fig. 1, the UPFC consists of three main components; the shunt converter, the series converter, and the coupling capacitor bank. Both shunt and series converters utilize VSCs fed from a common DC voltage of a capacitor bank. Shunt converter is used to provide the active power demand for the series converter. However, the reactive power can't be exchanged between both converters as they are coupled only with a DC link [5]. Thus, each converter is responsible for controlling the reactive power flow at its side.

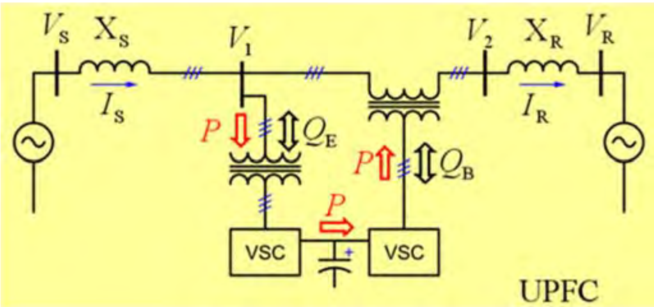

Fig. 1. Unified Power Flow Controller (UPFC) Model [6]

The normal active and reactive power flows through an uncompensated transmission line i – j are given by (1) and (2) respectively:

$$P_{ij} = \frac{V_i V_j}{X_{ij}} \sin(\delta_i - \delta_j) \quad (1)$$

$$Q_{ij} = \frac{V_i(V_i - V_j \cos(\delta_i - \delta_j)}{X_{ij}} \quad (2)$$

As shown in (1) and (2), the active and reactive power flows are depending on the line voltage magnitudes, line phase angle difference, and the line impedance. The aim of the UPFC is to control the line parameters to achieve many requirements. The requirements include (but not limited to) the following objectives:

- Minimization of the overall active power losses of the entire system
- Minimization of the overall cost of the system (both initial and operating costs)
- Optimization of the voltage controllability of the system
- Improvement of the generation system dispatching
- Mitigation of the system instabilities (both voltage and transient instabilities)

For the steady state analysis, the UPFC is modeled by the power injection model. The power injection model of the UPFC is shown in Fig. 2.

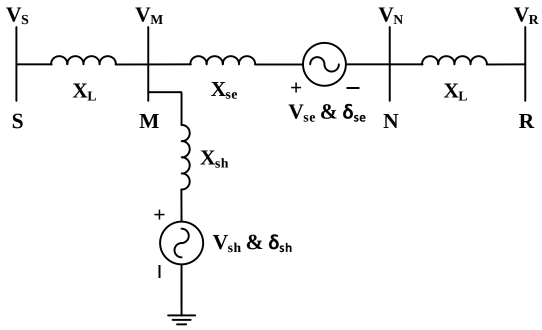

Fig. 2. Power Injection Model of UPFC [7], [3]

In the injection model, each of the shunt and series converters are modeled by a voltage source with controllable magnitude and phase angle in series with an impedance. By controlling the switching patterns of the shunt and series VSCs, the active and reactive power transfer through the UPFC can be independently controlled.

In order to achieve the prescribed control objectives, a multi-objective fitness function should be formulated and then optimized to get the optimum parameters of the UPFC system. Many optimization techniques are being used in literature to search for the best solutions for various optimization problems. Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony, Bee Colony, and Differential Evolution (DE) are examples of the most commonly-used optimization techniques in power system applications. In this paper, GA is used for the optimization of the UPFC location in the system.

III. Genetic Algorithm Optimization

One of the most powerful and practically-used global-searching optimization techniques is the Genetic Algorithm (GA). Genetic Algorithm is inspired from the natural selection process and is used as a search tool for complex optimization problems. The working principle of the GA consists of three steps; reproduction, natural selection, and diversity of the species (population) [14].

In this paper,

IV. Optimum Design of UPFC

In this analysis, the objective is to find the optimum location of the UPFC device that achieves the minimum overall system cost. System cost consists of UPFC investment cost (i.e., initial or fixed cost) and active power losses cost (i.e., running cost). In the following subsections, the fitness function that involves both costs is formulated and minimized subject to the system constrains to find the best location of the UPFC.

A. *Generation Cost Minimization*

The power generation cost for conventional generation units (i.e., gas and steam units) is usually modeled by a quadrature polynomial cost function as in (3) [15]:

$$C_1(P_{Gi}) = \sum_{i=1}^{n}(a_0 + a_1 P_{Gi} + a_2 P_{Gi}^2) \quad (3)$$

Where,

$C_1(P_{Gi})$ is the total generation cost of the system (in $), n is the total number of generation units, a_0, a_1 *and* a_2 are constant coefficients of the unit (in $, $/MW, and $/MW^2 respectively), and P_{Gi} is the power generation of one unit (in MW).

B. UPFC Investment Cost Minimization

The investment cost of the UPFC device is assumed to be modeled based on the following formula:

$$C_2 = \sum_{i=1}^{n} k * |S_{ij}|$$

Where,

S_{ij} is the total apparent power passing between buses i and j respectively.

C. Active Power Loss Minimization

The active power losses cost of the entire system is assumed to be modeled based on the following formula:

$$C_3 = \sum_{i=1}^{n} real\left(|S_i - S_j|\right)$$

Where,

S_i *and* S_j are the total apparent power entering buses i and j respectively.

D. Overall Flowchart of the Multi-objective Optimization of UPFC Location

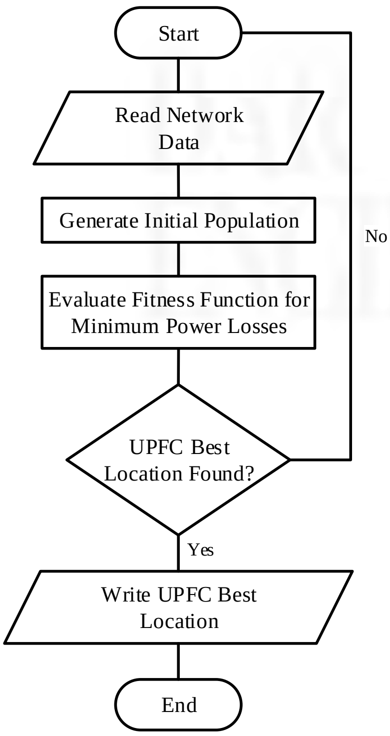

Fig. 3. Flowchart for the Optimum Allocation of UPFC Device [16]

V. REAL CASE STUDY IN SAUDI ARABIA

Fast-growing electrical power demand is a challenge that faces almost all countries all over the world. One of the most fast-growing electrical power networks is the Saudi Arabian National Grid (NG/SA). The rate of increase of the electrical power demand in NG/SA networks is extremely high, and that requires a continuous upgrading of the generation, transmission, and distribution networks. For that reason, NG/SA intended to increase the power transmission capability between the central and western transmission operating areas (COA and WOA respectively).

Accordingly, NG/SA has launched a project named Fixed Series Compensation (FSC) for installation of fixed series capacitors on the midpoint of the 380 kV double circuit transmission line between MADINAH-EAST and QASSIM-2 substations [8]. The double circuit line length between MADINAH-EAST and QASSIM-2 substations was 416.2 km before the installation of the FSC substation. Although after the insertion of the FSC substation at the midpoint of the double circuit line, it is divided into two (2) double circuit lines, each of 208.1 km (the length will be approximated to 200 km for ease of analysis). The main equipment required for FSC installation are described as follows [8]:

- Three (3) each: 130.5 MVAR (391.5 MVAR total 3-phase), 31.1 Ω, 1-phase capacitor bank units (the reactance will be approximated to 30 Ω for ease of analysis).
- Three (3) each: 1-phase Metal Oxide Varistor (MOV) units.
- Three (3) each: 1-phase triggered spark gaps.
- Three (3) each: 1-phase damping device.
- Three (3) each: 3150 A, dead tank, 1-phase, 380 kV, bypass circuit breaker (C.B.).
- Lot of disconnecting switches, earthing switches, surge arrester …etc. that are required to complete the one and half C.B. scheme of the substation.

The protection system provided for each of the four (4) transmission lines is described as follows [9]:

1. Set-1 (Main-1) is 7SD522, SIEMENS type multifunction Intelligent Electronic Device (IED).
2. Set-2 (Main-2) is P546, ALSTOM type IED.
3. Optical fiber cable communication is used to for exchanging of the digital aiding communication signals such as inter-tripping, blocking, permissive …etc.

The overall schematic diagram for the main and remote end substations is shown in Fig. 4 and Table I.

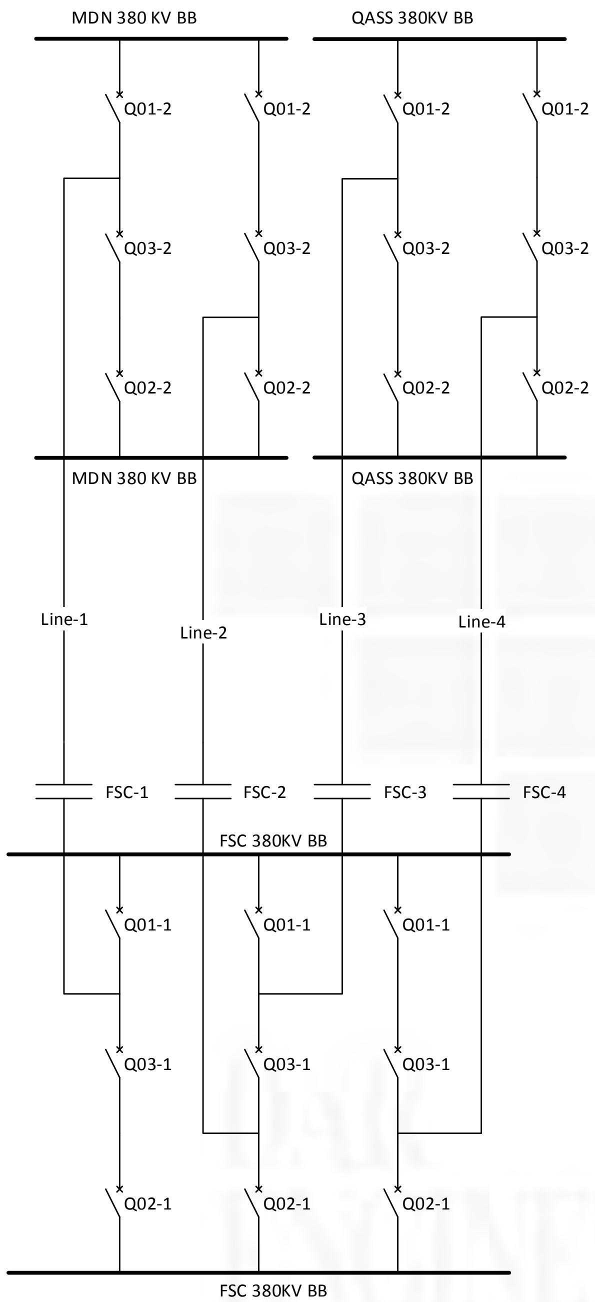

Fig. 4. Overall Single Line Diagram of FSC Real System

TABLE I
CASE STUDY SYSTEM PARAMETERS

Parameter	Value	Unit
System Voltage	380	kV
X/R Ratio	50	Ω/Ω
Short Circuit Level	63	kA
Positive Seq. Source Impedance	0.07 + j 3.482	Ω/ph.
Line Length (S – M or M – R)	200	km
Positive Seq. Line Impedance	0.013 + j 0.934e-3	Ω/km/ph.
Series Capacitor Rated Power	474.4	MVAR
Series Capacitor Rated Current	2255	A
Series Capacitor Reactance	31.098	Ω/ph.
Series Capacitor Capacitance	85.29	µF/ph.
Series Compensation Degree	50	%

VI. Distance Protection Challenges in Series-Compensated Transmission Lines

The simplified compensated system using fixed compensation and the proposed UPFC is shown in Fig. 5.a and 5.b. For the fixed compensation case, the compensated line reactance is plotted versus distance as illustrated in Fig. 6 to formulate the impacts of series capacitor on the distance relays. With the presence of series compensation, the measured reactances at relays S, M towards S, M towards R, and R are subject to a negative offset with a value equals to the series compensation capacitor reactance (≈ 30 Ω). The offset is negative when the series capacitor is in front of the relay and positive when the series capacitor is behind the relay (negative reactance is multiplied by negative sign due to reverse direction).

Consequently, the distance relays S, M towards S, M towards R, and R will be subjected to underreaching or overreaching depending on the relay and fault locations. This mal-operation was actually expected by the protection engineers during relay setting.

Detailed distance protection challenges are presented in the following sections [5], [6], and [10]:

1) Underreaching Challenge

Distance relays at FSC substation (M towards S, M towards R) will not be able to cover up to 96.37 km of the line (approximately 46.3 % of the line length) as the fault reactance will be negative at the relaying point up to that distance.

2) Blocking Scheme Challenge

Distance relays at FSC substation (M towards S, M towards R) will not be able to work in the reverse direction for blocking scheme as the fault reactance will be negative at the relaying point due to adjacent series capacitor bank of the other line.

3) Overreaching Zone Setting Challenge

The overreaching zone (zone 2) setting of distance relays at remote-end substations (S and R terminals) will be less than the main zone (zone 1) due to the negative reactance of series capacitor bank at the end of the line.

Due to the aforementioned major challenges, it was actually decided to totally disable the distance relaying function in the first and second main relays and keep only the differential and directional earth fault functions. This is the actual relay configuration at site till now. That means loosing of the main features of distance relaying such as loosing of fault location algorithm, loosing of the ability to clear high impedance faults by distance relay that cannot be detected by differential relay (due to the capacitive line charging compensation setting that requires a significant current setting offset in differential relay).

Moreover, by disabling distance relaying function, the backup protection (overreaching zones 2, 3, 4, 5, reverse zone, and non-directional starting zone) to adjacent lines, transformers and bus bars are also lost.

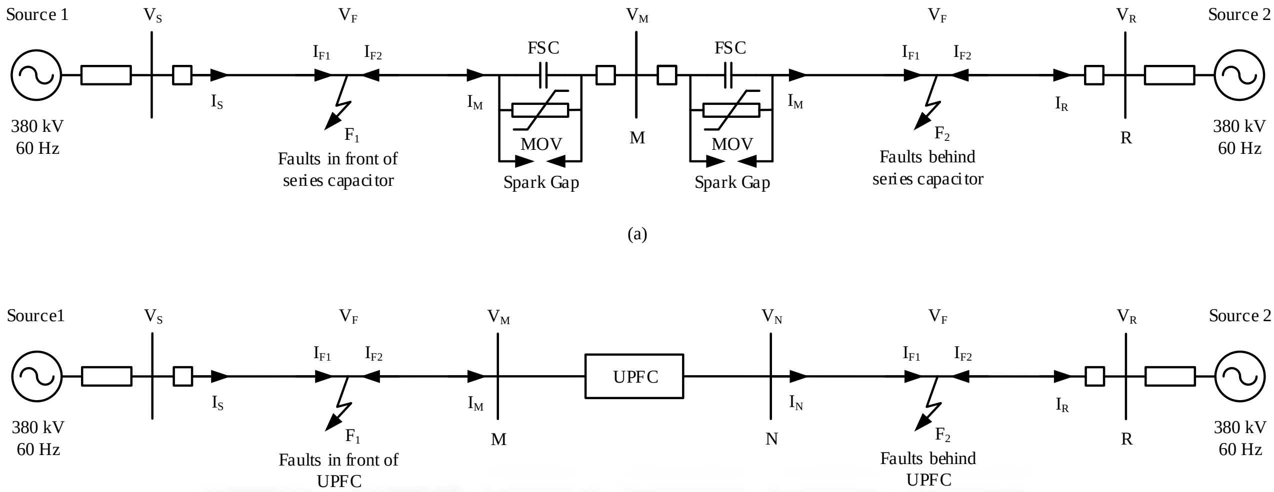

Fig. 5. Overall Compensated System using FSC and UPFC

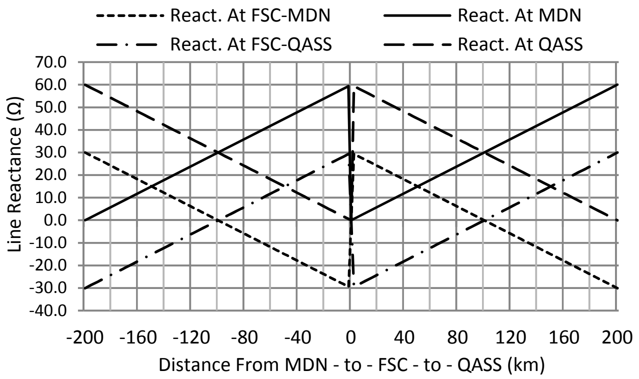

Fig. 6. Compensated reactance measured at each terminal

These significant needs and challenges for the operation of distance relay in fixed series-compensated transmission lines may be eliminated in UPFC-compensated system. This is because that the UPFC can be controlled to have zero-impedance value (i.e., as a bypass action) during faults to eliminate the aforementioned effects on the distance relay. This may mitigate the compensation effects on the existing protection systems.

VII. Conclusion and Future Work

From the previous discussion, the advantages of replacing the existing FSC compensation by a UPFC are assessed and verified. A comprehensive comparison between both solutions is given in Table II.

TABLE II
COMPARISON BETWEEN FSC AND UPFC COMPENSATION

Parameter	FSC	UPFC
Compensation Modes	Single Mode	Multiple Modes
Controllability	Limited	Versatile
Complexity	Simple	Complex
Stability Enhancement	Limited	Excellent
Capital Expenditures (CAPEX)	Low	High
Operational Expenditures (OPEX)	Low	Moderate
Maintenance	Low	Moderate
Impacts on Protection System	Minor	Major

Recommended future work is to investigate the superior controllability of the UPFC device via multi-objective optimization techniques. This multi-objective optimization techniques can achieve most (or maybe all) of the desired operational performance of the power system.

VIII. Acknowledgment

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X. BIOGRAPHIES

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