Real Finnish Network Reliability and Performance Enhancing by Optimal UPFC

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Abstract**—**UPFC has an efficient feature to control some of the network parameters as the active power flow, reactive power flow, and voltage magnitude at the UPFC installation buses. Using UPFC, the performance of the power system during various operating conditions can be improved. In this paper, a Genetic Algorithm (GA) is used to find the optimal location and the optimal UPFC parameters setting to enhance the transmission lines overloading issue keeping the voltage profile inside the enhanced limits. Additionally the outage cost of the power system is used to verify the impact of the optimized UPFC on the reliability. The application of this procedure is proposed on Helsinki HELENSÄHKÖVERKKO 110 KV NETWORK, which is a real Finnish world 110-kV sub transmission network with operating conditions of the present year until the year 2020. To show the validity of the technique, it will be tested first on the IEEE 6-bus system. The impact of UPFC installation in Helen network on the reliability in terms of outage costs will be discussed.

Keywords**—**Fitness Function, Genetics Algorithm (GA), Outage Cost, Optimal Placement.

I. Introduction

Unified Power Flow Controller (UPFC) is considered as a powerful device of the Flexible Alternating Current Transmission Systems (FACTS) family, where it has both a shunt and a series controller inside its frame. Therefore, UPFC has the ability to do both of Static VAR Compensator (SVC) and Static Synchronous Series Compensator (SSSC) performance simultaneously [1]. Alternatively, the controller may be set to control one or more of these parameters in any combination or to control none of them [2]. First phase of research in this area was focused on developing suitable models of UPFC, proposing control strategy and studies related to system stability enhancement [3]. UPFC allows not only the combined application of phase angle control with controllable series reactive compensations and voltage regulation, but also the real-time transition from one selected compensation mode into another one to damp oscillations and to handle particular system contingencies more effectively [4]. Furthermore, the utilization of UPFC technologies can have positive impacts on power system transmission reliability performance [5].

The real and reactive power flows in the transmission line are influenced by both the amplitude and the phase angle of series compensation voltage, therefore the change in real power can significantly effect the level of reactive power flow and it will be an interaction between the real and reactive power flows [6]. The Series reactive compensation could be replaced by phase-angle control or vice versa to achieve the required criteria [7]. This may become especially important when relatively large numbers of FACTS devices will be used in interconnected power systems, and control compatibility and coordination may have to be maintained in the face of equipment failures and system changes [8]. UPFC also provides considerable operating flexibility by its inherent adaptability to power system expansions and changes without any hard-ware alterations [9]. UPFC can be alternative to reduce the flows in heavily loaded lines, resulting in an increased loadability, low system loss, improved stability of the network [10]. Loading conditions, configuration of the system and the current operating point of the system are the main factors, which define the normal operation of the power network [11]. This paper concerns with increasing loadability of the grid and violation of bus voltage profile. Load increasing studies on the system can be applied at different cases and aspects. UPFC in optimal placement can restore the system operating condition to steady state point. Also the impact of the optimal location of the UPFC within a real world 110-kV-sub transmission power system on reliability is analyzed and the actual benefit is emphasized. The reliability calculation is based on both the normal and the outage contingency configuration of the system with increased loading pattern. Since the consideration of substations in composite reliability analysis is of high importance [12], the substations are included in this analysis.

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II. Problem Formulation

A. GA and Fitness Function

The normal operation of the power network depends on many factors as the loading conditions, the configuration of the system and the current operating point of the system. All the pervious factors affect the stability and the performance of the system.

Some indices will be used to show power line overloadings and bus voltage violations. After determining the performance indices, GA technique is applied to find the optimal location and parameters settings of UPFC. Installation of UPFC in such optimal criteria can eliminate or minimize the overloading of lines and the bus voltage violations while increasing the loadability. Therefore, the task is finding the optimal location and the optimal parameters setting of the UPFC in the power network to eliminate or minimize the overloaded lines and the bus voltage violations.

The main general description of the optimized equation is

$$\text{Min Fitness } F_t(X,U) \tag{1}$$

with subject to:

$$G_t(X,U) = 0.0 \quad , \quad H_t(X,U) \le 0.0 \tag{2}$$

where

$F_t(X,U)$ represents the fitness function to be minimized;

$G_t(X,U)$ represents the vector of the equality constraints corresponding to active and reactive power balance equations;

$H_t(X,U)$ represents the vector of the inequality constraints corresponding to UPFC parameter bounds limits, active and reactive power generation limits, bus voltage limits and phase angles limits;

X represents the vector of the state of the power system consisting of voltage magnitudes and phase angles.

U represents the vector of considered optimizable control variables, the location of UPFC and its parameters setting.

The fitness function depends on some performance indices. These fitness function and the performance indices will be changed according the scope zone of interest in the optimization process:

$$F_t(X,U) = \sum_{i=1}^{nbb} V(BV) + \sum_{j=1}^{ntl} L(OL) \tag{3}$$

$$V(BV) = \begin{cases} 0 & , if\ 0.95 \le V_i \le 1.05 \\ \log\left(\Psi_{V(BV)} \cdot \left| \dfrac{V_{i\,nominal} - V_i}{V_i} \right|^Q \right) & , otherwise \end{cases}$$

$$L(OL) = \begin{cases} 0 & , if\ S_{j,operating} \le S_{j,\max rate} \\ \log\left(\Psi_{L(OL)} \cdot \left(\dfrac{S_{j\,operating}}{S_{j\max rate}} \right)^R \right) & , if\ S_{j,operating} > S_{j,\max rate} \end{cases}$$

where

$V(BV)$ the Bus Voltage Violation function

V_i the voltage magnitude for each bus

$V_{i\ nominal}$ the bus nominal voltage for each bus

$\Psi_{V(BV)}$ the weight which is determined in order to have a certain weight value for the various percentage of voltage difference, also used to adjust the slope of the logarithm

Q the coefficient which is used to penalize more or less voltage variations

nbb the number of the buses in the system

$L(OL)$ the Over Loaded Line function

$S_{j\ operating}$ the current apparent power in line j

$S_{j\ max\ rate}$ the apparent power rating of line j

$\Psi_{L(OL)}$ the weight which is used in order to have a certain weight value for the various percentage of line loading, also used to adjust the slope of the logarithm

R the coefficient is used to penalize overloads and

ntl the number of lines in the system

Additionally some simulations the log relations can be replaced with linear relations, according to the penalty of overloading and voltage violations values.

B. UPFC Modeling for Power Flow

The equivalent circuit of an UPFC, shown in Figure 1, is attached with power system equations, and programmed in Matlab for results output. It consists of two synchronous voltage sources (SVS), which are simultaneous coordinated together to achieve the required performance mode [13].

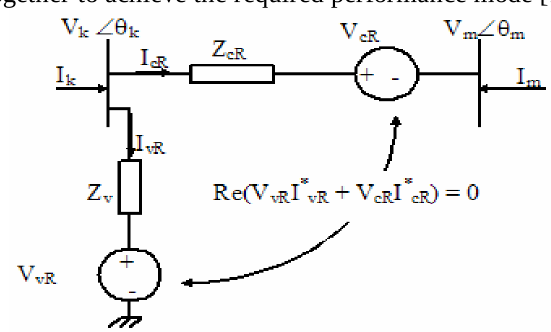

Fig. 1. UPFC equivalent circuit

The transmission line current flows through these voltage sources resulting in real and reactive power exchange between them and the ac system. The exchanged real power at the ac terminal is converted by an inverter into dc power. The exchanged reactive power at the ac terminal is generated internally by the inverter [14].

The UPFC equations can be summarized as follow

$$E_{vR} = V_{vR} * (\cos\delta_{vR} + j\sin\delta_{vR}) \tag{4}$$

$$E_{cR} = V_{cR} * (\cos\delta_{cR} + j\sin\delta_{cR}) \tag{5}$$

where

V_{vR} the magnitude of the shunt SVS voltage

δ_{vR} the value of the shunt SVS angle

V_{cR} the magnitude of the series SVS voltage and

δ_{cR} the value of the series SVS angle.

The active and reactive power equations for bus k and m can be combined with (4) and (5) to get:

$$P_{cR} = V_{cR}V_k(G_{km}\cos(\delta_{cR}-\theta_k)+B_{km}\sin(\delta_{cR}-\theta_k)) + V_{cR}V_m(G_{mm}\cos(\delta_{cR}-\theta_m)+B_{mm}\sin(\delta_{cR}-\theta_m))+V_{cR}^2G_{mm} \quad (6)$$

$$Q_{cR} = V_{cR}V_k(G_{km}\sin(\delta_{cR}-\theta_k)-B_{km}\cos(\delta_{cR}-\theta_k)) + V_{cR}V_m(G_{mm}\sin(\delta_{cR}-\theta_m)-B_{mm}\cos(\delta_{cR}-\theta_m))-V_{cR}^2B_{mm} \quad (7)$$

$$P_{vR} = -V_{vR}^2G_{vR}+V_{vR}V_k(G_{vR}\cos(\delta_{vR}-\theta_k)+B_{vR}\sin(\delta_{vR}-\theta_k)) \quad (8)$$

$$Q_{vR} = V_{vR}^2B_{vR}+V_{vR}V_k(G_{vR}\sin(\delta_{vR}-\theta_k)-B_{vR}\cos(\delta_{vR}-\theta_k)) \quad (9)$$

where

V_k *and* V_m the voltage magnitudes at bus k and bus m

θ_k *and* θ_m the voltage angles at bus k and bus m

P_{cR} *and* Q_{cR} the series SVS active and reactive powers

P_{vR} *and* Q_{vR} the shunt SVS active and reactive powers

G_{mm}, G_{kk} , G_{km} , G_{mk} the conductance elements, related to lines between buses *k* and *m*

B_{mm}, B_{kk} , B_{km} , B_{mk} the susbtance elements , related to lines between buses *k* and *m* and

G_{vR}, B_{vR} , G_{cR}, B_{cR} the susbtances and conductances for shunt and series SVS.

C. Performance Index

For applying UPFC installation, the optimal locations and optimal parameters setting (V_{cR}, V_{vR}) will be adjusted by the designed Genetics Algorithm (GA) which will be shown later.

The installations of UPFC will be performed on the system during the normal and the outage contingency operation while increasing the loading pattern. For each operating condition, the following performance indices will be used:

- Ḱ(LOLN): the index which indicates the Lines Over Loaded Number
- Γ(VBVN): the index which indicates the Buses Voltage Violation Number and
- Performance Index Я = Ḱ(LOLN) + Γ(VBVN)

Where Я is zero for the case that there is no overloading on power lines and no violations in bus voltage.

D. Reliability Analysis

The sub transmission reliability calculation is based on the frequency and duration approach [15] and it is performed with an AC-load flow from NEPLAN [16], including first and second order faults. The UPFC is integrated in the 110-kV-sub transmission grid based on the UPFC model in [17] with two additional circuit breakers. The failure rate and repair time of the UPFC are 0.02 f/yr and 60 hours respectively from [5]. All generators in the grid are assumed to be ideal in the sense of reliability.

The single line diagram of the 110-kV-sub transmission grid in Figure 3 has been extended with four different substation types from [18]. The exact substation type of each node, including the number of modeled HV/MV-transformers (equal to the number of loads), can be found in Figure 3 and Table 1. Outage costs and the Outage Cost Function (OCF) from [19], based on the expected energy not delivered, are used to quantify the benefit of the UPFC in the grid. These outage costs, listed in Table I, do not consider the ability of switching at medium voltage substations but the outage costs consider congestion management in terms of load shedding.

The used reliability data - only long independent outages and common mode faults are considered in the calculation - for each modeled component is listed in Table 2. Disconnectors are assumed to have no outages. The considered time dependent overload capability (OLC) of the overhead lines and cables is additionally listed in Table 2.

Table (I) OCF, Substation type (ST) for each load point; D: Double busbar, S: Single busbar, H: upper H-connection and B: Block-connection

Bus, ST	OCF = k·x+d		Bus, ST	OCF = k·x+d	
	k	d		k	d
	€/kW	€/kWh		€/kW	€/kWh
1, D	0.92	9.34	13, H	2.28	22.47
2, D	2.90	23.46	14, H	2.28	22.47
3, D	2.28	22.47	15, S	2.28	22.47
4, D	1.88	18.43	16, B	2.28	22.47
5, D	1.88	18.43	17, S	1.88	18.43
6, D	0.92	9.34	18, S	1.88	18.43
7, D	0.66	7.32	19, H	1.88	18.43
8, D	2.90	23.46	20, H	1.88	18.43
9, S	0.92	9.34	21, H	1.88	18.43
10, H	1.38	13.38	22, S	2.28	22.47
11, H	1.38	13.38	23, H	2.28	22.47
12, H	1.38	13.38	24, S	2.28	22.47

Table (II) Reliability Component Data of the grid; μl … average repair time for long independent outages; λl … average failure rate for long independent outages

Component 110 kV	μ_l	λ_l	OLC in %	
	h	1/a km, 1/a	11 min	1 h
Circuit Breaker	100	3.36E-03	100	100
Busbar	200	6.80E-03	100	100
Transformer 110/20	300	3.00E-03	150	150
Overhead Line	48	4.00E-04	120	105
Cable	336	1.00E-03	120	105
Common mode	48	1.00E-04	–	–

III. Proposed Genetics Algorithm

While applying GA to solve a particular optimization problem, the following issues need to be addressed: representation of the solution variables and the objective (fitness) function [20].

In the GA, the individuals are coded to a chromosome that contains variables of the problem. The configuration of chromosome in order to optimal location of the UPFC consists of two types of parameters: location of UPFC and parameters setting (V_{cR}, V_{vR}) as decoupled model parameters of UPFC. In Figure 2, the chromosome for the proposed algorithm is shown.

Objective Function	….	Location of UPFC ($UPFC_{tln}$)	V_{cR}	V_{vR}

Fig. 2 Chromosome of proposed GA

- The first set of chromosomes (first chromosome) in the individual represents the locations of UPFCs devices in the network. This set contains the indices of the lines where the UPFCs should be located.

- The second set (starting from the end of the first set) represents the value of V_{cR} for the series SVS. The range for this set is randomly generated within the working range [0.001, 0.3].

- At last, the third set (starting form the end of the second set) represents the value of V_{vR} for the shunt SVS. The range for this set is randomly generated within the range [0.8, 1.2].

A genetic algorithm is governed by three factors: mutation rate, crossover rate and population size. The GA is a search process, which can be applied to constrained problems [21]; the constraints may be included into the fitness function. In this algorithm, optimization issues that must be performed on the objective function and all equality and inequality constraints including the UPFC equations [22], should be included the problem.

The architecture of the GA implementation can be segregated into the following three constituent phases, namely: Initial population generation, fitness evaluation and genetic operations.

Table (III), Designed Values for the GA

GA Parameters	
Input Variables	x(1)= UPFCtln x(2)= Vcr(1) x(3)= Vvr(1)
Variables Lower bound	LB = [1 0.001 0.8];
Variables Upper bound	UB = [ntl 0.3 1.2];
Options. PopulationType	Double Vector
Options. PopulationSize	Adapted in simulations
Options. EliteCount	Adapted in simulations
Options. CrossoverFraction	Adapted in simulations
Options. MigrationDirection	Forward
Options. MigrationInterval	20
Options. MigrationFraction:	0.2
Options. Generations	Adapted in simulations
Options. TimeLimit	Inf
Options. FitnessLimit	-Inf
Options. StallGenLimit	50
Options. StallTimeLimit	Inf
Options. TolFun	1e-6
Options. TolCon	1e-6
Options. InitialPenalty	10
Options. PenaltyFactor	100
Options. FitnessScalingFcn	‘Rank’
Options. SelectionFcn	‘Stochastic Uniform’
Options. CrossoverFcn	‘Scattered’
Options. MutationFcn	@mutationadaptfeasible

IV. Simulation Results

A. Scope of the Simulations Files

Matlab Codes for GA (with the main GA file, the fitness function file and the constraints file) and a modified power flow algorithm to include UPFC were developed. Programmed M-files are incorporated to include the updates for each individual in each population for adjusting the algorithm according to the required indices and terms.

This procedure is proposed to be tested on the test system, an IEEE 6-bus system and then applied on a real world 110-kV-sub transmission grid: Helsinki HELEN SÄHKÖ VERKKO 110 KV NETWORK.

B. Application Results on IEEE 6-Bus System

For the validation of the proposed techniques, it had been tested on the following test system, an IEEE 6-bus system (shown in Figure 3) [23].

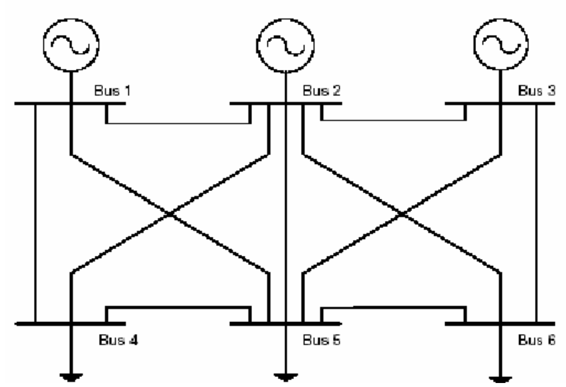

Fig. 3 The IEEE 6-Bus System.

This system consists of three generators, six buses, eleven transmission lines, and three loads. During the results, Y1 will penalize the value of overall overloading for all lines of the system and Y2 will penalize the value of overall voltage violations for all buses of the system. The calculations for Y1 and Y2 will depend on terms in (3). The loading pattern will be increased in uniform rate to create the overloading of the transmission lines, starting from one overloading for one transmission line and so on for multiple overloading in the system.

Table (IV). IEEE 6-Bus System, case study 1

➔ Increasing Load Pattern at all Load buses with 143 %

➔ Before UPFC installation

Ḱ$_{(LOLN)}$=1	Y1=0.16	Γ$_{(VBVN)}$=0	Y2=0	Я =1	Y=Y1

Overloaded Line 1-2	112.38 %

➔ Optimal UPFC installation

➔ Optimal location: line 1-2, optimal setting: (0.024,1.191)

Ḱ$_{(LOLN)}$=0	Y1=0	Γ$_{(VBVN)}$=0	Y2=0	Я =0	Y=0

➔ No overloading, no voltage violation $0.95 \le V_i \le 1.05$

Table (V). IEEE 6-Bus System, case study 2

➔ Increasing Load Pattern at all Load buses with 145 %

➔ Before UPFC installation

Ḱ$_{(LOLN)}$=2	Y1=0.3	Γ$_{(VBVN)}$=0	Y2=0	Я =2	Y=Y1

Overloaded Line 1-2	115.2 %
Overloaded Line 1-5	102 %

➔ Optimal UPFC installation

➔ Optimal location: line 1-2, optimal setting: (0.008, 1.19)

Ḱ$_{(LOLN)}$=0	Y1=0	Γ$_{(VBVN)}$=0	Y2=0	Я =0	Y=0

➔ No overloading, no voltage violation $0.95 \le V_i \le 1.05$

Table (VI). IEEE 6-Bus System, case study 3

➔ Increasing Load Pattern at all Load buses with 148 %

➔ Before UPFC installation

Ḱ$_{(LOLN)}$=3	Y1=0.41	Γ$_{(VBVN)}$=0	Y2=0	Я =3	Y=Y1

Overloaded Line 1-2	118.04 %
Overloaded Line 1-4	101 %
Overloaded Line 1-5	102.77 %

➔ Optimal UPFC installation

➔ Optimal location: line 1-4, optimal setting: (0.042, 1.194)

Ḱ$_{(LOLN)}$=0	Y1=0	Γ$_{(VBVN)}$=0	Y2=0	Я =0	Y=0

➔ No overloading, no voltage violation $0.95 \le V_i \le 1.05$

From the previous tables, we can find that all line overloading are eliminated by placing UPFC in an optimal location with optimal parameters setting by GA. While for bus voltage profile, the optimal location and settings resulted from the GA keep the voltage profile for all the buses in the system inside the required limit.

In order to show the impact of the reliability, by optimized settings at the optimal position, a reliability analysis is performed without UPFC (woUPFC) and with UPFC (wUPFC), both taking into account the component data of Table 2 for the average repair time and overloading capability of power lines. The average failure rate is set to 0.1 for all power lines. Disconnectors, circuit breakers and busbar are assumed to be ideal. Based on the grid and load data of the IEEE 6 bus test-system [24], with each of the three load buses having a OCF similar to bus 2 in Table 1 the following results are obtained by the reliability calculation

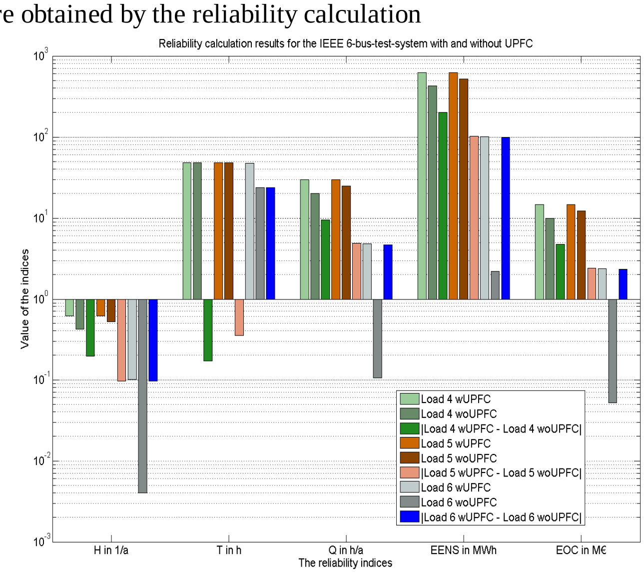

Fig. 4. Comparison of reliability calculation results for the IEEE 6-bus test-system wUPFC and woUPFC

The installation of the UPFC at the reliability-optimized location with optimal settings has an influence on the line outage of power line between bus 1 and bus 4. If this line is outaged, no overloading of other power lines occurs and hence no load curtailment has to be used in order to reduce this overloading. Furthermore, compared to the IEEE 6 bus test-system without UPFC, also no overloading occurs, when power line three from bus 1 to bus 5 and power line 6 from bus 2 to bus 5 is outaged. All these relevant aspects, decrease for example the reliability index outage probability (H) at bus 4 to 6, decrease the non-availability (Q), the expected outage costs (EOC) and the expected energy not supplied (EENS) also at buses 4 to 6. These improvements result in an overall EOC decrease of 10.52 M€ per anno which indicates, assuming validity of all assumptions like used outage costs, loading conditions, reliability data, power system configuration and so on, that the installation of an UPFC is economically justifiable with repayment of investment costs within certain years.

In order to verify these results, the GA algorithm is now applied on a real world sub-transmission power system.

C. Application Results on a Finnish Sub-transmission Network

The data, configuration, loading and generation patterns of a real world 110-kV-sub transmission grid; Helsinki HELENSÄHKÖVERKKO 110 KV NETWORK are available in [24]. Also the configuration of the network is depicted in Figure 5.

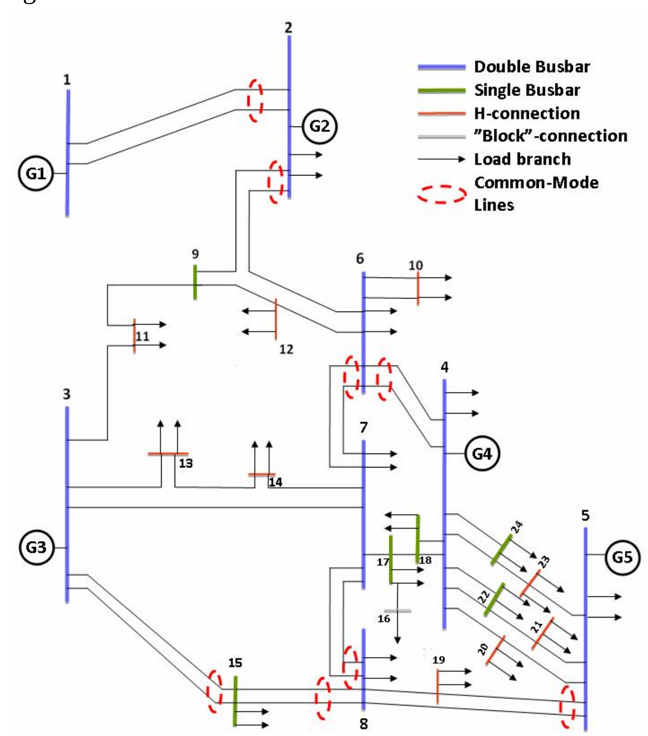

Fig. 5. Configuration of applied network

The load and generation data is provided through Helsinki University of Technology. The data was measured hourly for twelve months in 2006. The applications of UPFC for this network will be studied until year 2020 using the load-forecasting coefficient, which is available for the year 2020.

To show the high effectiveness of the UPFC installation, the design of the UPFC will be applied for the worst case, which is the highest loading value at each bus, for all the buses at the same time. This procedure will be applied for present loading pattern and also for worst case of year 2020.

Increasing load patterns will be performed with two procedures, the first one is multiplying all the entire loads in the system by increasing with a specified percentage factor. The second one is multiplying all the entire loads in the system by its individual forecasted load coefficient for the considered year 2020.

Estimating loadability of a power transmission network has practical importance in power system operations and planning. Increasing the loadability of the system will be indicated during the analysis to measure the utilization of the network after the UPFC installation.

The simulation results show that UPFC can be used to enhance loadability in some cases at the power system even with one; two or more lines are overloaded. Y1 will penalize the value of overall overloading for all lines of the system and Y2 will penalize the value of overall voltage violations for all buses of the system. The calculations for Y1 and Y2 will depend on the terms in equation (3).

The results show that the UPFC can significantly improve the performance of power systems with optimal location and optimal parameter settings. Placing UPFC in the system eliminates all of the overloaded lines. The algorithm is able to reach the solution space eliminating the overloaded lines and at the same moment keeping the voltage profile constraint. Increasing of transmission system loadability of a power system as an index to evaluate the impact of UPFC in power system is achieved in some cases with respect to the line flow limits and the bus voltage magnitude limits.

D. Reliability Study Results

To verify the effect of the optimal UPFC location and settings on reliability with different loading scenarios, the annualized expected outage costs are calculated with the load duration approach [17] using the load and generation characteristics in [24].

Therefore, the procedure will start to indicate the performance indices without UPFC in the network. Then apply GA to install the UPFC at optimal placement with optimal settings.

Table (VII) 110-kV case study 1

→Max. Load for all buses at the same time with 115 % increase

→ Before UPFC installation

Ḱ$_{(LOLN)}$=0	Y1=0	Γ$_{(VBVN)}$=0	Y2=0	Я =0	Y=0
Loadability			30.26 %		

→ After UPFC installation

→ Optimal line 6-4, optimal setting: (0.004, 0.934)

Ḱ$_{(LOLN)}$=0	Y1=0	Γ$_{(VBVN)}$=0	Y2=0	Я =0	Y=0
Loadability			31.45 %		

→ No overloading, no voltage violation 0.98≤V_i≤1.02

Table (VIII) 110-kV case study 2

→Max. Load for all buses at the same time with 118 % increase

→ Before UPFC installation

Ḱ$_{(LOLN)}$=1	Y1=0.12	Γ$_{(VBVN)}$=0	Y2=0	Я =1	Y=Y1
Loadability			31.52 %		
Overloaded Line 9-2			102.96 %		

→ After UPFC installation

→ Optimal location: line 11-3, optimal setting: (0.137, 1.196)

Ḱ$_{(LOLN)}$=0	Y1=0	Γ$_{(VBVN)}$=0	Y2=0	Я =0	Y=0
Loadability			34.88 %		

→ No overloading, no voltage violation 0.98≤Vi≤1.02

Table (IX) 110-kV case study 3

→Max. Load for each bus at the same time multiplied by 98 % of 2020 coefficient [25]

→ Before UPFC installation

Ḱ$_{(LOLN)}$=1	Y1=0.15	Γ$_{(VBVN)}$=0	Y2=0	Я =1	Y=Y1
Loadability			32.30 %		
Overloaded Line 9-2			110.42 %		

→ After UPFC installation

→ Optimal location: line 12-9, optimal setting: (0.203, 0.885)

Ḱ$_{(LOLN)}$=0	Y1=0	Γ$_{(VBVN)}$= 0	Y2=0	Я =0	Y=0
Loadability			35.6 %		

→ No overloading, no voltage violation 0.98≤Vi≤1.02

Table (X) 110-kV case study 4

→Max. Load for each bus at the same time multiplied by 100 % of 2020 coefficient [25]

→ Before UPFC installation

Ḱ$_{(LOLN)}$=2	Y1=0.21	Γ$_{(VBVN)}$=0	Y2=0	Я =2	Y=Y1
Loadability			35.40 %		
Overloaded Line 9-2 & 6-2			101.00 % & 102.00%		

→ After UPFC installation

→ Optimal location: line 12-9, optimal setting: (0.215, 0.988)

Ḱ$_{(LOLN)}$=0	Y1=0	Γ$_{(VBVN)}$=0	Y2=0	Я =0	Y=0
Loadability			36.3 %		

→ No overloading, no voltage violation 0.98≤V_i≤1.02

These characteristics, based on unequal spaced time intervals, are derived from the load and generation duration curve of the 8760 hourly measured values. The results, comparing the annualized expected outage costs, based on the forecasted load of the year 2020 in [24] and case study 4, with and without the UPFC, are depicted in Figure 6.

The following stage will concern with solving the problem of the network related to overloading of transmission lines and violation of bus voltage profile on the contingency operation of transmission lines outage. We use the Genetics Algorithm (GA) to find the optimal location and the optimal settings of UPFC to improve the performance of the power system at the contingency of the transmission line outage.

Table (XI) 110-kV Outage case study

→ Outage of Line (9-12) and Before UPFC installation

Ḱ$_{(LOLN)}$=1	Y1=0.17	Γ$_{(VBVN)}$=0	Y2=0	Я =1	Y=Y1
Loadability			27.88 %		
Overloaded Line 6-2			115.21 %		

→ After UPFC installation

→ Optimal line 11-3, optimal setting: (0.239, 0.9525)

Ḱ$_{(LOLN)}$=0	Y1=0	Γ$_{(VBVN)}$=0	Y2=0	Я =0	Y=0
Loadability			29.4468 %		

→ No overloading, no voltage violation 0.98≤Vi≤1.02

Comparing the expected annualized total outage costs of the considered network, including load curtailment at all buses in order to clear power line overloading or load flow convergence problems in the calculation algorithm, based on the optimized position and settings of Table 11, without UPFC (119624616 €) with the expected total outage costs (126713869 €) of the considered grid containing the UPFC at the optimal location, an increase of expected annualized outage costs can be observed. This enhancement is caused by several overloading conditions, different to the power system without UPFC, that requires load curtailment. Contrary to the overall EOC increase in the power system, there is a decrease in the overall outage probability H (wUPFC: 0.822 1/a; woUPFC 0.842 1/a) and overall non-availability Q (wUPFC: 7541 min/a; woUPFC: 7614 min/a). However, the power system configuration with the load point specific outage costs forces that there is already a difference of 15573379 € in EOC if only single outages are considered in the power system reliability analysis. Moreover, the main contribution to expected annualized outage costs is from single station originated outages where the optimal settings and location of the UPFC has no impact on reliability improvement.

In Table 12, the differences of woUPFC calculation results and wUPFC calculation results for outage probability H, outage duration T, non-availability Q and energy not supplied EENS are summarized. The results show that, similar to the EOC in Figure 6, that installing UPFC in this real power system, increases EOC, EENS, Q and H at load buses 5, 7, 19, 20, 21 and 23. This is the region in the power system with high outage costs where load curtailment affects these reliability indices.

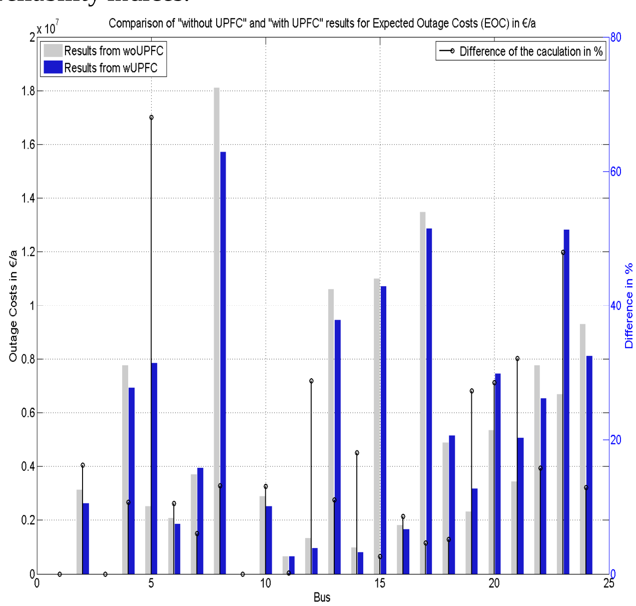

Fig. 6 Calculation Results of the reliability analysis comparing the 110-kV sub transmission grid with and without UPFC for the year 2020.

Table (XII) Difference between woUPFC and wUPFC reliability results for the proposed power system in % grey marked: value of wUPFC is greater than value of woUPFC

ST	H	T	Q	EENS	ST	H	T	Q	EENS
	%					%			
1	0	0	0	0	13	7	6	13	11
2	29	18	14	16	14	22	5	17	18
3	0	0	0	0	15	5	0	5	3
4	21	11	10	10	16	14	11	4	9
5	72	22	64	68	17	6	1	5	5
6	21	12	10	10	18	3	8	5	5
7	12	8	5	6	19	18	6	23	27
8	15	0	16	13	20	31	8	25	29
9	0	0	0	0	21	33	10	25	32
10	19	7	13	13	22	22	10	13	16
11	0	0	0	0	23	52	17	43	48
12	39	15	27	29	24	17	4	13	13

However, it is not a general statement that, UPFC affects the reliability with this negative impact [25], it depends obviously on the network parameters like outage costs, type of substations, loadability, intermeshing degree and so on; and we will study that in an upcoming paper.

V. Conclusion

The results show that the UPFC can significantly improve the performance of power systems with optimal location and optimal parameter settings. Placing UPFC in the system eliminates all of the overloaded lines. While the algorithm is able to reach the solution space to eliminate the overloaded lines, it keeps the voltage profile within its limits. Increasing of transmission system loadability of power system as an index to evaluate the impact of UPFC in power system is achieved in most of cases with respect to the line flow limits and the bus voltage magnitude limits.

With the IEEE 6 bus test-system is has been demonstrated that optimal location and settings of UPFC devices can significantly increase the overall reliability of a transmission power system.

Although the installation of the UPFC device decreases the outage probability of the real world power system, it increases the expected outage costs. The real world system shows impressively, that it is necessary to analyze the impact of an UPFC on reliability indices in detail, since the shifted load flow can also have negative aspects on for instance expected outage costs and expected energy not supplied. Also the GA algorithm is applied through the outage contingency configuration; and achieves the required performance.

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