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A Practical Approach for Coordinated Transmission Switching and OLTCs' Tap Adjustment: DIgSILENT-Based Improved PSO Algorithm

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Abstract- *Transmission lines switching and tap adjustment of power transformers are short-term alternatives to enhance the flexibility of power system operation. By a proper implementation of these alternatives, the operational problems such as lines congestion, bus voltage violations and excessive power losses can be alleviated. Traditionally, these two alternatives are applied separately due to the complexity of their simultaneous implementation as well as their coordination. In this paper, a DIgSILENT-based improved particle swarm optimization (IPSO) algorithm is proposed to implement the transmission switching and coordinated voltage control of power transformers, concurrently. The IPSO is implemented in DPL environment of Powerfactory-DIgSILENT, as a powerful software package commonly used by the electrical utilities. The proposed approach is applied to IEEE-14 bus system and the real transmission network of Zanjan Regional Electric Company (ZREC) located in Iran, in different scenarios considering all the existing practical constraints. The obtained results verify the effectiveness of the presented approach.*

Keyword: Transmission system switching, OLTC's tap adjustment, Improved PSO, DIgSILENT

NOMENCLATURE

A. Indices and sets

i , B	Index of buses
ℓ	Index of lines
t	Index of transformers
Ω_B	Set of network buses
Ω_i	Set of buses connected to bus i through a line
Ω_B^G	Set of generation buses
Ω_t	Set of network transformers
Ω_ℓ	Set of network lines

B. Parameters and variables

OF	Objective function
f_{Loss}	Objective function of power loss
f_{Loss}^0	Network power loss before optimization
$f_{Loading,Tr}$	Objective function of transformers loading
$f_{Loading,Tr}^0$	Transformers loading before optimization
$f_{Loading,total}$	Objective function of total loading
$f_{Loading,total}^0$	Total loading before optimization
$Ploss_\ell$	Power loss of line ℓ
$Ploss_t$	Power loss of transformer t
S_ℓ	Loading percent of line ℓ
S_t	Loading percent of transformer t
$Penalty$	Penalty for not satisfaction of problem constraints
VP_i	Penalty of bus i's voltage violation form its acceptable range
LP_t	Penalty of transformer t's loading violation form its acceptable value
LNS_i	Load of isolated substation i
LP_ℓ	Penalty of line ℓ's loading violation form its acceptable value
P_{G_i}, Q_{G_i}	Generated active and reactive powers at bus i
P_{D_i}, Q_{D_i}	Demand active and reactive powers at bus i
$\lvert V_i \rvert, \delta_i$	Magnitude and angle of voltage of bus i
$\lvert Y_{ij} \rvert, \theta_{ij}$	Amplitude and angle of admittance of line between buses i and j
Tap_t	Tap position of power transformer t

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$P_{G_i}^{max/min}$	Maximum/minimum active power of generator *i*
$Q_{G_i}^{max/min}$	Maximum/minimum reactive power of generator *i*
$Tap_t^{max/min}$	Maximum/minimum tap position of power transformer *t*
$V^{max/min}$	Maximum/minimum voltage of buses
S_ℓ^{max}	Capacity of line ℓ
S_t^{max}	Capacity of transformer t

1. INTRODUCTION

1.1. Motivation

Transmission network as a major part of power system plays an important role in reliable delivery of electric energy from generation centers to consumers located in distribution networks. With ever increasing electricity consumption, power passing through the transmission system is consequently increased causing congestion in transmission lines/power transformers and unacceptable voltage drops in the network [1]. This condition reveals the need for reinforcing the transmission infrastructure through the construction of new lines/transformers and upgrade of the existing equipment [2, 3]. The network reinforcement is a challenging option due to high equipment installation costs, long construction period, right-of-way and environmental concerns [1]. Therefore, optimal use of existing transmission capacities usually gains the attention of network operators. Transmission lines switching and tap adjustment of power transformers are some short-term alternatives in order to improve the operation flexibility of power systems [4, 5]. Enhancement of operation flexibility of a power system is also known as the system's power flow control [6]. Compared to the network capacity reinforcement, these alternatives are low-cost and more accessible solutions for adding more flexibility to operation of transmission systems. Transmission lines switching (known also as transmission network reconfiguration) refers to changing the open/close status of lines that is employed for fulfilment of different objectives such as congestion relief, generation cost minimization, power loss reduction, and voltage profile improvement [4]. Tap adjustment of power transformers plays a vital role in voltage control as well as optimal reactive power flow in the network that results lines loading management and power loss reduction [7]. Traditionally, due to complexity of simultaneous implementation, these two operational flexibilities are applied separately, while their coordinated utilization will bring more improvement in the network operation than their separated implementation.

1.2. Literature review

Several researches with different optimization algorithms have been presented for optimal operational planning of transmission systems through optimal transmission switching (OTS) or voltage control of transformers. The lines switching is usually called as "Transmission Switching (TS)" in transmission systems and "Reconfiguration" in distribution networks.

Many researches have addressed the lines reconfiguration in distribution networks for the purpose of power loss reduction, voltage profile improvement, lines overload relief, reliability and resiliency enhancement [8-12]. Variety of works have also been implemented around transmission switching. A stochastic optimization model has been presented in Ref. [13] for the security-constrained unit commitment (SCUC) integrating the OTS for handling the uncertainty of wind power generation and equipment failures including the outage of lines or generating units. The interdependency between two power flow control methodologies including transmission switching and variable-impedance series FACTS devices has been investigated in Ref. [14]; a formulation for co-optimization of FACTS and TS operation is conducted where the generation dispatch, FACTS set point, and switching schedules are optimized simultaneously. The simulation results verify that higher cost savings can be achieved when hybrid operation of FACTS and TS is considered instead of separate deployment of each technology. This study has used the DC model for power flow. A multi-objective approach for congestion management (CM) is presented in Ref. [15] through the OTS considering minimization of total operating cost and maximization of probabilistic reliability as two conflicting objectives. The transmission lines for the switching actions are determined via a security-constrained ac optimal power flow, and the solution of optimization problem is implemented using the combination of evolutionary and stochastic programming approaches.

Some other researches have focused on voltage control of transmission networks. An opposition-based self-adaptive modified gravitational search algorithm (OSAMGSA) has been presented in Ref. [16] for optimal reactive power dispatch and voltage control in transmission systems. The tap position of tap changing transformers, generators' voltages, and reactive power of shunt capacitors are the decision variables. The aim is to optimize network power losses, voltage deviation, and voltage stability index. A coordinated control framework has been proposed in Ref. [7] to handle negative impacts of voltage resulted from wind power generation in a weak sub-transmission system. If the control actions of traditional voltage regulators such as on-load tap changers (OLTCs) and capacitor banks cannot meet the control requirements, an event-triggered load-side aggregate controller is activated immediately to assist for voltage regulation. In Ref. [17], the OLTCs, capacitor banks, and load shedding (LS) are coordinated in order to provide emergency voltage control in transmission system in an adaptive manner. In Ref. [18], an automatic OLTC control scheme has been developed for power transformers. The proposed strategy uses the changes of voltage and current on high-voltage side of the transformer, resulting from OLTC operation, to monitor the OLTC stability by estimating an index. A two-level voltage control is presented in Ref. [19] for large-scale power systems. The controller aims to provide a near-optimal voltage profile in the transmission system by coordination of discrete reactive power control equipment in the network. The VAr sources include shunt capacitor banks, reactors and OLTCs. The considered control is fulfilled in two levels: local substation controls and a central coordinator located at the control center. Reference [5] offers a security and optimization rule-based generator Simultaneous Tap Change Dispatch (STCD) strategy to preserve the system wide-area voltage stability via effective and fast voltage regulation. The strategy also reduces total amount of reactive power utilization leading to minimization of power losses. Also, a comparison is made between the cost of MVAr utilization and the use of new shunt reactors.

1.3. Contributions

By reviewing the aforementioned literature, the following issues can be concluded:

- Few researches have considered simultaneous implementation of TS and tap adjustment of power transformers;
- To the best of the authors' knowledge, no study has been presented so far to implement the coordinated tap adjustment and TS in DIgSILENT-Powerfactory and to carry out the optimization within this software;
- The previous works have not considered the practical aspects of the power system. These aspects will be described in the following.

In this paper, a new approach is proposed for simultaneous TS and tap adjustment of OLTCs. Power systems are modelled in DIgSILENT-Powerfactory software as a powerful package with precise models of equipment and accurate calculations of power system studies using the AC power flow model. As mentioned, when using the DIgSILENT, a complete model of power system equipment can be considered, such as lines' geometrical model, conductors' structural model (bundles, skin effect, environment temperature), transformers' core and copper losses models, generators' active/reactive power limits, etc. The proposed problem is formulated as an optimization problem where an improved particle swarm optimization (IPSO) algorithm is employed to solve it. The IPSO is implemented via DPL capability of the DIgSILENT, that eliminates the need for additional optimization software such as MATALB or GAMS. Different objective functions are defined, and all of the practical constraints of the network are considered, precisely. Thus, the main contributions of this paper can be listed as follows:

- Simultaneous implementation of TS and OLTCs' tap adjustment.
- Using an improved PSO algorithm as the optimization algorithm.
- Implementation of the proposed optimization problem in DIgSILENT as a practical and frequently-used commercial software by the power system engineers.
- The proposed approach does not require other optimization software, as the optimization is carried out within DIgSILENT.
- Consideration of the practical limits and constraints of the system.
- Applying the proposed approach on the real-life transmission system of ZREC in addition to IEEE 14-bus system.

1.4. Paper structure

The reminder of this paper has been organized as follows:

The proposed problem is formulated in Section 2. Section 3 presents the solution algorithm for the proposed optimization problem. Numerical results are prepared in Section 4. Finally, Section 5 concludes the paper.

2. PRROBLEM FORMULATION

2.1. Objective functions

Three main objectives are regarded in the proposed optimization model. The first objective is to reduce the active power loss of the network as Eq. (1):

$$min \left\{ f_{Loss} = \sum_{\ell \in \Omega_\ell} Ploss_\ell + \sum_{t \in \Omega_t} Ploss_t \right\} \quad (1)$$

Where, $Ploss_\ell$ and $Ploss_t$ are the power loss of line ℓ and transformer *t*, respectively. The power loss of transformers, in turn, includes no-load (core loss) and load loss (copper loss). Ω_ℓ and Ω_t are the set of lines and transformers, respectively.

The second objective function includes loading of HV/MV power transformers as Eq. (2). Where P_t, Q_t, and S_t are the active, reactive, and apparent powers flowing through transformer *t*, and $S_{t,rated}$ is the rated capacity of transformer *t*.

$$min\left\{ f_{Loading,Tr} = \sum_{t\in\Omega_t} S_t \right\} \qquad (2)$$
$$S_t = \frac{|P_t + jQ_t|}{S_{t,rared}}$$

The third objective function is the loading of all equipment including transformers and lines as (3), where S_ℓ is the ratio of passing apparent power to the rated capacity of line ℓ.

$$min\left\{ f_{Loading,total} = \sum_{\ell\in\Omega_\ell} S_\ell + \sum_{t\in\Omega_t} S_t \right\} \qquad (3)$$

The above objective functions are combined as the following:

$$min\ OF = k_1 \times \left(\frac{f_{Loss}}{f^0_{Loss}}\right) + k_2 \times \left(\frac{f_{Loading,Tr}}{f^0_{Loading,Tr}}\right) + k_3 \times \left(\frac{f_{Loading,total}}{f^0_{Loading,total}}\right) + Penalty \qquad (4)$$

In Eq. (4), the three objective functions are combined where each of them are normalized through dividing them to their initial value. f^0_{Loss} , $f^0_{Loading,Tr}$, and $f^0_{Loading,total}$ are the initial values of objective functions for the base case (before the optimization). The coefficients k_1, k_2, and k_3 are determined by the network operator to select his desired objective function. They should be given 1 or 0 for regarding or disregarding the corresponding objective function. For example, for minimization of transformers loading, the planner selects these coefficient as $(k_1,k_2,k_3)=(0,1,0)$. The '*penalty*' in Eq. (4) is violation value of problem constraints from their acceptable ranges. These constraints include voltage and loading limitations and also, the load not supplied due to the reconfiguration process. The penalty is defined as Eq. (5):

$$Penalty = \sum_{i\in\Omega_B} VP_i + \sum_{t\in\Omega_t} LP_t + \sum_{\ell\in\Omega_\ell} LP_\ell + \sum_{i\in\Omega_i} LNS_i \qquad (5)$$

In Eq. (5), the voltage penalty (VP) is used as Eq. (6):

$$VP_i = \begin{cases} 0 & if\ 0.95 \le |V_i| \le 1.05 \\ 10\times(|V_i| - 0.95) & if\ |V_i| < 0.95 \\ 10\times(1.05 - |V_i|) & if\ |V_i| > 1.05 \end{cases} \qquad (6)$$

where, the factor 10 is used as a weighting factor. In Eq. (6), $|V_i|$ denotes the voltage magnitude of bus *i*. Also, the lines' and transformers' loadings penalty (LP) are determined Eqns. (7) and (8), where S^{max}_ℓ and S^{max}_t are the allowed values of lines and transformers.

$$LP_\ell \begin{cases} 0 & if\ S_\ell \le S^{max}_\ell \\ S^{max}_\ell - S_\ell & if\ S_\ell > S^{max}_\ell \end{cases} \qquad (7)$$

$$LP_t \begin{cases} 0 & if\ S_t \le S^{max}_t \\ S^{max}_t - S_t & if\ S_t > S^{max}_t \end{cases} \qquad (8)$$

The last term in Eq. (5) is the load not supplied (LNS). If a substation is isolated subject to reconfiguration, the isolated load is multiplied to a big number, and considered in the objective function. By this way, the particles with isolated substations will be omitted in the next generations and the final solution is one with no isolated substation.

2.2. Decision variables

As mentioned earlier, the problem is to simultaneously optimize the transmission lines' configuration and power transformers' tap settings. Therefore, the decision variables shown by *X* in Eq. (9) consist in two sets. The first set shows the voltage set-point of power transformers in per-unit. These set-points will accordingly determine the tap position of transformers as the automatic tap changing feature has been activated in DIgSILENT. *ct* is the number of candidate transformers whose set-points (tap positions) are to be optimized. Also, the second set includes the state of lines which is a binary variable being 0 if the line is open (out-of-service), and is 1 if the line is closed (in-service). *cl* is the number of candidate lines that can be switched.

$$X = \left[\overbrace{SP_1, SP_2, \ldots SP_{ct}}^{Voltage\ Set\ Points},\ \overbrace{SP_1, SP_2, \ldots SP_{ct}}^{Voltage\ Set\ Points} \right] \qquad (9)$$

2.3. Constraints

The considered problem is subjected to some technical limitations as Eqns. (10)-(15). Relations (10) and (11) are the active and reactive power balance in buses based on AC power flow calculations. Relations (12) and (13) denote the active and reactive power generation limits of generators. Relation (14) shows the acceptable voltage range of buses, and Eq. (15) represents the tapping range of power transformers. Finally, Eq. (16) represents the loading limitation of lines and transformers

$$P_{G_i} - P_{D_i} = |V_i| \sum_{j \in \Omega_i} |V_j||Y_{ij}| \cos(\delta_i - \delta_j + \theta_{ij}) \quad ; \quad \forall i \in \Omega_B \tag{10}$$

$$Q_{G_i} - Q_{D_i} = |V_i| \sum_{j \in \Omega_i} |V_j||Y_{ij}| \sin(\delta_i - \delta_j + \theta_{ij}) \quad ; \quad \forall i \in \Omega_B \tag{11}$$

$$P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max} \quad ; \quad \forall i \in \Omega_B^G \tag{12}$$

$$Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max} \quad ; \quad \forall i \in \Omega_B^G \tag{13}$$

$$V^{min} \le |V_i| \le V^{max} ; \quad \forall i \in \Omega_B \tag{14}$$

$$Tap_t^{\min} \le Tap_t \le Tap_t^{\max} \quad ; \quad \forall t \in \Omega_t \tag{15}$$

$$\begin{aligned} &S_\ell \le S_\ell^{\max} \forall \ell \in; \quad \Omega_\ell \\ &S_t \le S_t^{\max} \forall t \in; \quad \Omega_T \end{aligned} \tag{16}$$

$$\begin{aligned} v_{id}(k+1) = \omega v_{id}(k) + c_1 r_1 (p_{id}(k) - x_{id}(k)) \\ + c_2 r_2 (g_d(t) - x_{id}(k))\} \end{aligned} \tag{17}$$

$$x_{id}(t+1) = x_{id}(t) + v_{id}(t+1) \tag{18}$$

$$\omega = \omega_{max} - \frac{(\omega_{max} - \omega_{min})}{iter^{max}} \times iter \tag{19}$$

$$c_1 = c_{1s} + \frac{(c_{1f} - c_{1s})}{iter^{max}} \times iter \tag{20}$$

$$c_2 = c_{2s} + \frac{(c_{2f} - c_{2s})}{iter^{max}} \times iter \tag{21}$$

3. PROBLEM SOLUTION

3.1. Improved particle swarm optimization

Regarding the objective functions and constraints, we are encountered with a complex non-linear optimization problem which requires an appropriate algorithm for the solution. In this paper, an efficient version of PSO algorithm has been employed for the sake of problem optimization.

PSO is a meta-heuristic optimization method that falls in the group of population-based algorithms. It was firstly introduced by Eberhart and Kennedy in 1995 [20], and since then, many modifications have been proposed for improving its performance. PSO has been inspired from the social behavior of animals like birds and fishes as the particles. Each particle is regarded as a potential solution of the problem which moves in a *D*-dimensional search space to search for the food position as the optimal solution. The particles exchange their experience with their neighbors to update their velocity and position aiming at reaching to the food source [20-22]. Compared to other algorithms, PSO has simpler procedure and fewer parameters to be adjusted. The best position experienced by a particle and the best position experienced by the whole particles (*g*) are used to update the velocity and position of particles as Eqns. (17) and (18).

In Eq. (17), $v_{id}(k)$ and $p_{id}(k)$ are the velocity and position of i^{th} particle in dimension *d* in movement stage of *k*; p_{id} is the best position experienced by particle *i* in dimension *d*, g_d is the best position experienced by the whole particle in dimension *d*; c_1 and c_2 are the acceleration coefficients; r_1 and r_2 are random numbers uniformly distributed in range [0,1]; and ω is the inertia coefficient.

In this paper, an improved version of PSO is employed in which ω is linearly decreased as a function of iteration (movement) number (*k or iter*) as Eq. (19) [23]. Also the parameters c_1 and c_2 follow the expressions Eqns. (20) and (21), where c_{1s} and c_{2s} are the starting values of c_1 and c_2, and c_{1f} and c_{2f} are their final values. With these modifications, PSO shows better performance and convergence trend compared to traditional version in which c_1 and c_2 are constant. In the classic PSO algorithm, the acceleration coefficients are set to fixed values (conventionally fixed to 2.0). The relative values of two acceleration coefficients (c_1 and c_2) control the local and global search ability of the algorithm. If the value of social component

c_2 is selected to be higher than the cognitive component c_1, then algorithm will be guided to a local optimum, prematurely. In the other hand, selection of a higher value for cognitive component (comparing to social component) will wander the particles around the search space. In the utilized IPSO, in initial iterations, the cognitive component value is higher which force the particles to wander around the search space. With proceeding the iterations, the value of social component is increased, which force the particles to attain an optimal solution. Adaptive update of acceleration coefficients improves the solution quality. In this paper, the values of ω_{max} and ω_{min} are considered 0.9 and 0.2, respectively. c_{1s} and c_{1f} are equal to 2.5 and 0.5, and c_{2s} and c_{2f} are given as 0.5 and 2.5, respectively. The number of particles has been considered as 10. In meta-heuristic algorithms like genetic algorithm (GA), PSO, etc., it cannot be claimed that the obtained results are optimal; however, by using several approaches, it is tried to get the best possible solution. In this paper, the optimization algorithm is run for several times to make sure of its convergence. As a single solution is obtained in several executions, it is ensured that the obtained solution is possibly optimal. In addition, in this paper, the best obtained solution in any given execution is considered as the initial population of the next execution, then the algorithm is run again to make sure of the solution's optimality.

3.2. Applying PSO to the proposed problem in DIgSILENT

For applying the PSO algorithm to the proposed optimization problem, the decision variables are encoded within the dimensions of particle. A typical particle has been depicted in Fig. 1. The considered particle is composed of two parts. In part 1, each dimension represents the voltage set-point of corresponding power transformer which is real number between 0.95 and 1.05pu. In part 2, the on/off status of candidate lines has been shown by a binary value, where 1 means the 'on' state (line is in circuit), and 0 shows 'off' state (line is out of circuit). Based on (12) and (13), as the PSO works real values, these values in part 2 of the particle are rounded to be converted to 0 or 1 [24, 25].

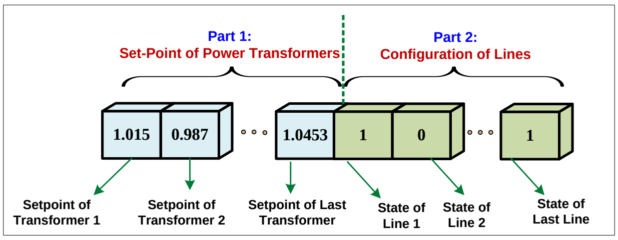

Fig. 1. Structure of a typical particle of PSO for the proposed problem

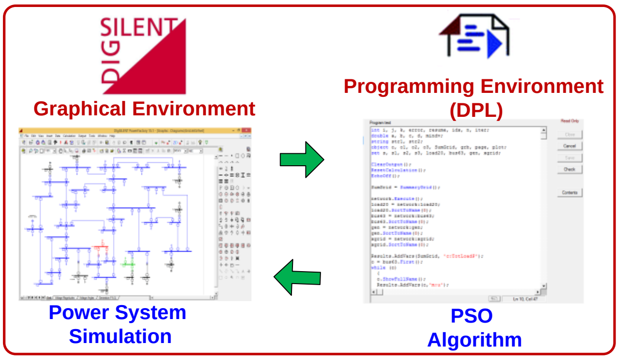

Fig. 2. Schematic view of optimization package

The proposed PSO algorithm has been programmed through DPL (DIgSILENT Programming Language) in programming environment of PowerFactory-DIgSILENT software and linked with power system model in the simulation environment. Fig. 2 shows a schematic view of the optimization package. Also, Fig. 3 summarizes the process of solving the proposed problem using the PSO algorithm in DIgSILENT software.

4. NUMERICAL STUDY

In this part, numerical studies of the proposed method are presented. At first, the modified IEEE 14-bus system is used to evaluate the efficiency of the presented approach with more detailed investigations. Then, the proposed approach is tested on a real and large-scale transmission system.

4.1. First system: modified IEEE 14-bus system

The data of IEEE 14-bus system is given in Ref. [26]. In this paper, some modifications have been made on this system such as defining the medium-voltage (MV) side for the network, changing the voltage levels, and adding a new line. This system has been illustrated in Fig. 4. The network has three voltage levels of 230kV, 63kV, and 20kV. The generators are in 230kV side, and the loads of buses 13-18 are located in 20kV side. All the transformers are equipped with on-load tap changer (OLTC). The transformers located on load buses 13-18 are high-voltage to medium-voltage (HV/MV) ones having 63kV/20kV voltage levels; their tap position must be adjusted to deliver 1p.u. voltage to the MV side (20kV). The transformers T1 and T2 are extra high-voltage to high-voltage (EHV/HV) ones having 230kV/63kV voltage level; they have the task of regulating the network voltage and controlling the power flow in the lines; their tap position are to be optimized by the PSO algorithm. The tap changers of EHV/HV transformers are located at EHV side and it controls the voltage of HV side. Also the OLTC of HV/MV transformers is located in HV side controlling the voltage of MV side. The OLTCs have 11 tap positions as ±5×2% and one neutral position.

The lines Line1-Line7 have voltage level of 230kV (EHV), and the lines Line8-Line16 are 63kV (HV) ones. The loading limit of lines and transformers are considered as 80%. Also, it is tried to maintain the buses voltage within the acceptable range, i.e. [0.95 1.05] pu. All the 63kV lines are candidates for switching (reconfiguration). The lines switching along with tap adjustment (voltage set-point) of EHV/HV transformers T1 and T2 are the operator's alternatives for fulfillment of his objectives including power loss reduction and relieving the lines and transformers high loadings. Therefore, the number of decision variables to be optimized by the PSO algorithm is 11. The proposed approach is applied to this system in the following scenarios.

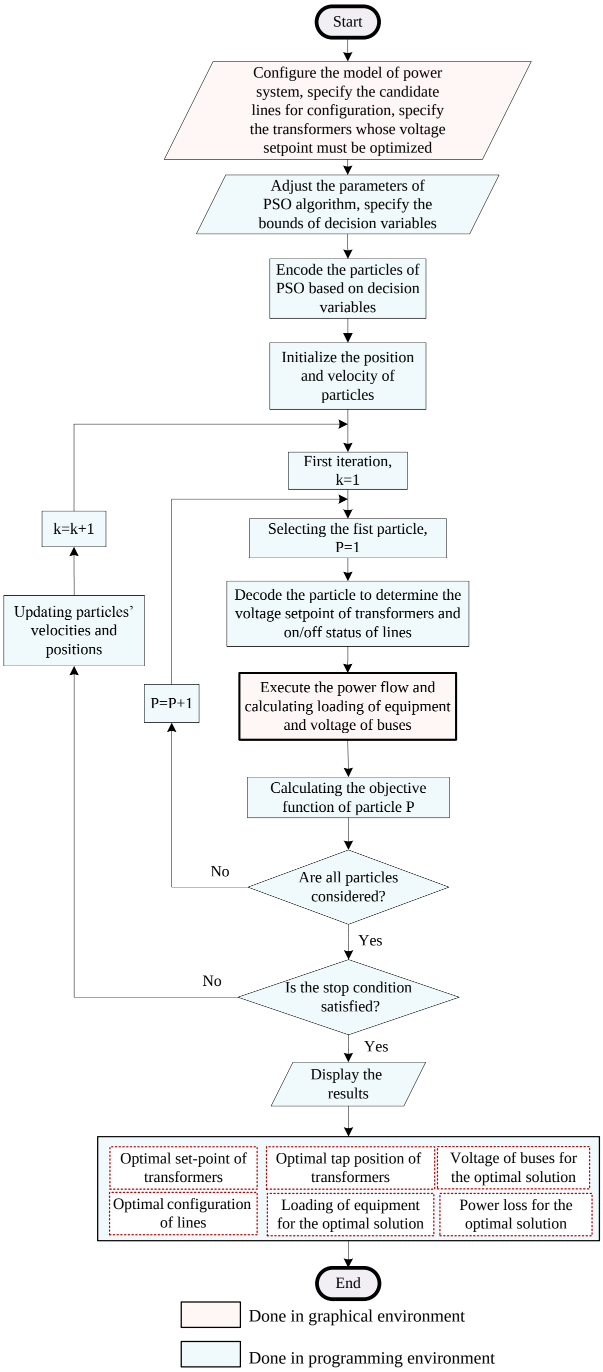

Fig. 3. Flowchart of the problem optimization

- **Scenario 1: Only tap adjustment of EHV/HV transformers:** In this scenario, the lines configuration is fixed, and the aim is to investigate the effect of tap setting of transformers T1 and T2 on the network's technical parameters.
- **Scenario 2: Only switching of HV lines:** In this scenario, the tap position of transformers T1 and T2 is fixed at -2, and the aim is to determine the optimal lines configuration to investigate its effect on the network's technical parameters.
- **Scenario 3: Simultaneous tap adjustment of EHV/HV transformers and switching of HV lines:** In this scenario, the lines configuration and tap adjustment of power transformers T1 and T2 are simultaneously optimized.

The proposed approach can be applied considering each of (1), (2), and (3) as the objective function. However, as the main parameter from the viewpoint of network operator is the power loss, in this part, only the results of power loss reduction as the objective are presented.

The obtained results have been presented in tables 1 to 5 and Figs. 5 to 7 for these three scenarios as well as the base scenario (before optimization). Table 1 summarizes the values of objective function components. In Table 2, the results of optimization have been given for the transformers. Table 3 presents the lines status in different scenarios. As seen, some lines have been switched off in scenarios 2 and 3 to satisfy the problem constraints. Table 4 gives the value of lines and transformers loadings, and Table 5 lists the bus voltage values in different scenarios.

In scenarios 0 and 1 (i.e. Sc.0 and Sc.2), where there is no tap optimization, the tap positions for transformers T1 and T2 have been fixed at -2. In the base scenario, the power loss is 27.57MW. It has been decreased to 26.44, 27.35, and 25.84MW in scenarios 1, 2, and 3, respectively. It is observed that in scenario 3 where both tap adjustment and reconfiguration are applied, the power loss reduction is more than other scenarios. The power loss reduction in this scenario is about 6.4%.

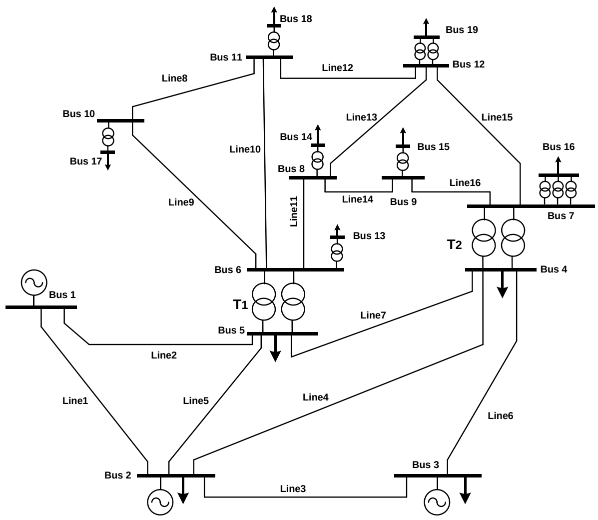

Fig. 4. Modified IEEE 14-bus system

Also, the sum of all equipment's loading shows the highest reduction in scenario 3 where it has been decreased from 789.43% to 707.76%. In the base scenario, there is a loading violation of 14.66% which is related to Line 11 in Fig. 4.

Table 1. The obtained results for objective function of power loss

No. Scenario	Description	f_{Loss} (MW)	$F_{Loading,Tr}$ (%)	$F_{Loading, total}$ (%)	Voltage Penalty(pu)	Lines Loading Penalty (%)	Transformers Loading Penalty (%)	Total Objective Function
		Output Results						
Sc.0	Before optimization	27.57	141.39	789.43	0.009	14.66	0	26.66
Sc.1	Tap	26.44	140.78	767.44	0	3.2	0	6.127
Sc.2	Reconfiguration	27.35	142.05	785.51	0.012	2.34	0	17.332
Sc.3	Tap+ Reconfiguration	25.84	139.51	707.76	0	0	0	2.820

Table 2. The obtained results for the transformers when the objective function is power loss reduction

Tr. No.	Optimization Results							
	Sc.0		Sc.1		Sc.2		Sc.3	
	Set point	Tap	Set point	Tap	Set point	Tap	Set point	Tap
Tr1	-	-2	1.0259	-4	-	-2	1.0467	-5
Tr2	-	-2	1.0122	-5	-	-2	1.0296	-5

Table 3. Lines switching results when the objective function is power loss reduction

Line No.	Line status (0: out ; 1:in)			
	Sc.0	Sc.1	Sc.2	Sc.3
Line 8	1	1	1	1
Line 9	1	1	1	1
Line 10	1	1	1	1
Line 11	1	1	1	1
Line 12	1	1	1	1
Line 13	1	1	1	1
Line 14	1	1	0	0
Line 15	1	1	1	0
Line 16	1	1	1	1

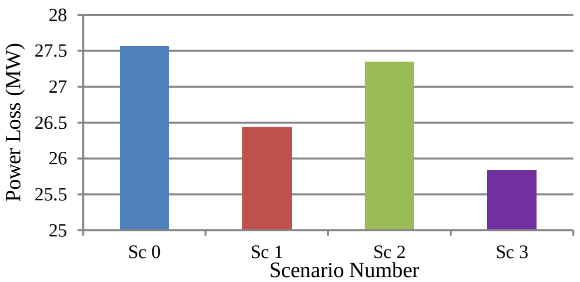

Fig. 5. Comparison of power loss for 14-bus system in different scenarios

As seen from Table 4, in the base scenario, the loading of Line 11 is 94.66% which is 14.66% above the acceptable loading limit (80%). However, the proper tap adjustment and lines switching have relived this high loading and has decreased it from 94.66% to 69.62% in scenario 3. According to Table 5, in the base scenario, the voltages of buses 7, 9, 12 are lower than 0.95 p.u while they have been improved in scenario 3 to the values greater than 1pu. In total, it is observed that the operation of network is more improved when tap adjustment and lines switching actions are coordinated. As the results show, the power loss is minimum in the third scenario; all the limitations are also satisfied in this scenario where the loading of all lines is below 80% and voltage of all buses is more than 0.95pu.

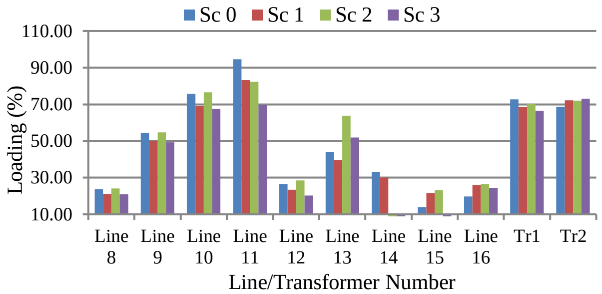

Fig. 6. Comparison of loading results for 14-bus system in different scenarios

Table 4. Loading of lines and transformers when the objective function is power loss reduction

Line No.	Loading (%)			
	Sc.0	Sc.1	Sc.2	Sc.3
Line 1	78.09	77.90	78.15	77.93
Line 2	57.39	57.10	57.30	56.84
Line 3	33.72	33.73	33.80	33.80
Line 4	26.88	26.93	27.03	27.03
Line 5	19.51	19.19	19.36	19.00
Line 6	13.06	13.10	13.02	12.83
Line 7	33.57	34.56	34.86	36.92
Line 8	23.70	21.04	24.15	20.87
Line 9	54.37	50.00	54.79	49.21
Line 10	75.68	69.10	76.60	67.55
Line 11	**94.66**	**83.20**	**82.34**	**69.62**
Line 12	26.60	23.34	28.38	20.29
Line 13	43.96	39.75	63.79	51.87
Line 14	33.15	30.06	0.00	0.00
Line 15	13.95	21.61	23.28	0.00
Line 16	19.74	26.03	26.63	24.48
Tr1	72.72	68.53	70.08	66.49
Tr2	68.67	72.25	71.97	73.02

4.2. Second system: real network of Zanjan Regional Electric Company (ZREC)

For evaluating the efficiency of the proposed approach, in addition to 14-bus system, it is also applied to real network of Zanjan Reginal Electric Company (ZREC) as a practical large-scale network. It should be noted that the prepared software has a generality to be applied to any network with different size and characteristics. The single-line diagram of this network has been illustrated in Figs. 8 and 9. As the size of network is large, its EHV, HV and MV parts have been separated to be shown in two figures. These parts are connected together as the similar names in the two figures show. ZREC includes the transmission and sub-transmission networks of two provinces of Zanjan and Ghazvin located in northwest of Iran. The ZREC is interconnected to four regional neighboring networks named Tehran, Azarbaijan, Gilan, and Bakhtar. Within the ZREC, there is one gas power plant with nominal generation capacity of 540MW, and also some distributed generation (DG) units with total capacity of 197MW. The gas power plant has been modeled as PV bus. One of the neighboring networks (Tehran) is modeled as slack (reference) bus, and the three others are modeled as PV buses. Also, the DG units have the model of PQ bus. The EHV voltage levels are 400kV and 230kV, HV one is 63kV, and the MV part is 20kV.

These voltage levels have been shown by different colors in Figs. 8 and 9. The number of 400kV/230kV, 400kV/63kV, 230kV/63kV, 230kV/20Kv, and 63kV/20kV substations are 2, 4, 9, 2, and 42, respectively. Due to the security concerns, the authors are not allowed to give the complete data of the network. For this reason, in Figs. 9 and 10, the real names of the substations have not been shown, and they are represented by some codes (S1, S2, …, S58). Also, the substation capacity as well as the tap changers' intervals is given in Table 6.

The aim is to apply the proposed method to relieve the loading of lines and transformers and minimize the power loss for peak loading condition of year 2019 through appropriate tap adjustment and line switching. The presented method can also be applied to any other operational conditions such as medium or low load conditions without any limitations. The total real load of network in the peak load condition of year 2019 was 1540MW and 607MVAr. This condition was occurred on June 31 at 12:58 p.m., and the real load data has been recorded by the measuring devices.

Table 5. Bus voltages when objective function is power loss reduction

Bus No.	Voltage (Pu)			
	Sc.0	Sc.1	Sc.2	Sc.3
Bus 1	1.05	1.05	1.05	1.05
Bus 2	1.011	1.011	1.011	1.012
Bus 3	0.988	0.988	0.988	0.989
Bus 4	0.985	0.985	0.984	0.986
Bus 5	0.99	0.991	0.99	0.991
Bus 6	0.971	1.026	0.973	1.047
Bus 7	**0.949**	1.012	0.947	**1.03**
Bus 8	0.951	1.01	0.954	1.029
Bus 9	**0.948**	1.01	0.945	**1.027**
Bus 10	0.959	1.015	0.96	1.035
Bus 11	0.951	1.008	0.952	1.028
Bus 12	**0.944**	1.005	0.946	**1.021**
Bus 13	0.991	1.005	0.992	1.005
Bus 14	1.001	0.999	1.004	0.998
Bus 15	0.992	0.993	0.989	1.011
Bus 16	0.999	1	0.997	0.997
Bus 17	1.007	1.002	0.987	1.002
Bus 18	0.995	1.013	0.997	1.011
Bus 19	1.008	1.007	0.988	1.003

Table 6. The data of substations and tap changers

Substation No.	Substation Name	Capacity (MVA)	Voltage Level (kV)	Tap Range	Set point side
1	S1	2×315	400/230	[1 19]	230
2	S2	3×200	400/230	[1 19]	230
3	S3	2×200	400/63	[1 19]	63
4	S4	2×200	400/63	[1 19]	63
5	S5	2×200	400/63	[1 19]	63
6	S6	2×200	400/63	[1 19]	63
7	S7	3×125	230/63	[-9 9]	63
8	S8	3×160	230/63	[-9 9]	63
9	S9	2×90	230/63	[-9 9]	63
10	S10	3×125	230/63	[-9 9]	63
11	S11	2×160	230/63	[1 19]	63
12	S12	3×90	230/63	[-9 9]	63
13	S13	2×160	230/63	[1 19]	63
14	S14	2×160	230/63	[-9 9]	63
15	S15	1×125	230/63	[1 19]	63

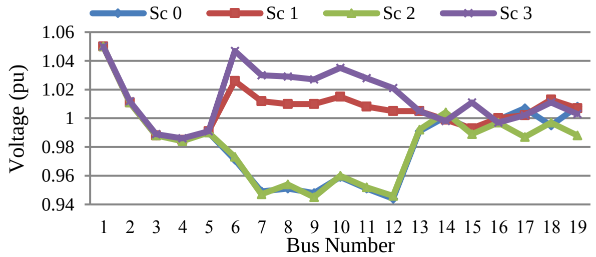

Fig. 7. Voltage profile of 14-bus system buses in different scenarios

The real data of ZREC network has been used in modeling of transformers, lines, generators, etc.; for example, lines geometrical characteristics (distances on the tower), magnetic coupling among the line circuits on the towers, ACSR (Aluminum Conductor Steel Reinforced) conductors' structural data (bundles, skin effect, environment temperature around the conductors), and generators' power capability curve. There are 15 substations which their voltage set-point should be optimized. These substations include 400kV/230kV, 400kV/63kV, and 230kV/63kV ones. The number of 63kV lines that can be switched is 80. These 80 lines have been selected based on real possibility of switching. That is to say, some lines cannot be switched on/off due to the protection relays considerations. By these data, there are 95 decision variables that must be optimized by the IPSO algorithm.

The optimization has been done considering the power loss reduction as the objective function in three scenarios mentioned before. In scenarios Sc0 and Sc2 in

Table 7. The obtained results for the objective function of power loss

Scenario	Description	Output Results							
		f_{Loss} *(MW)*	$f_{Loading,Tr}$ *(%)*	$f_{Loading,total}$ *(%)*	*NBL**	*Voltage Penalty(pu)*	*Lines Loading Penalty (%)*	*Transformers Loading Penalty (%)*	*Total Objective Function*
Sc. 0	Before optimization	50.51	1195	7594	11	1.018	0	0	13.18
Sc. 1	Tap	49.93	1179	7457	11	0.7548	0	0	10.51
Sc. 2	Reconfiguration	48.44	1173	7698	9	0.3101	0	0	6.06
Sc. 3	Tap+Reconfiguration	48.34	1157	7851	2	0.0589	0	0	3.55

***** Number of EHV and HV buses with voltages lower than 0.95pu

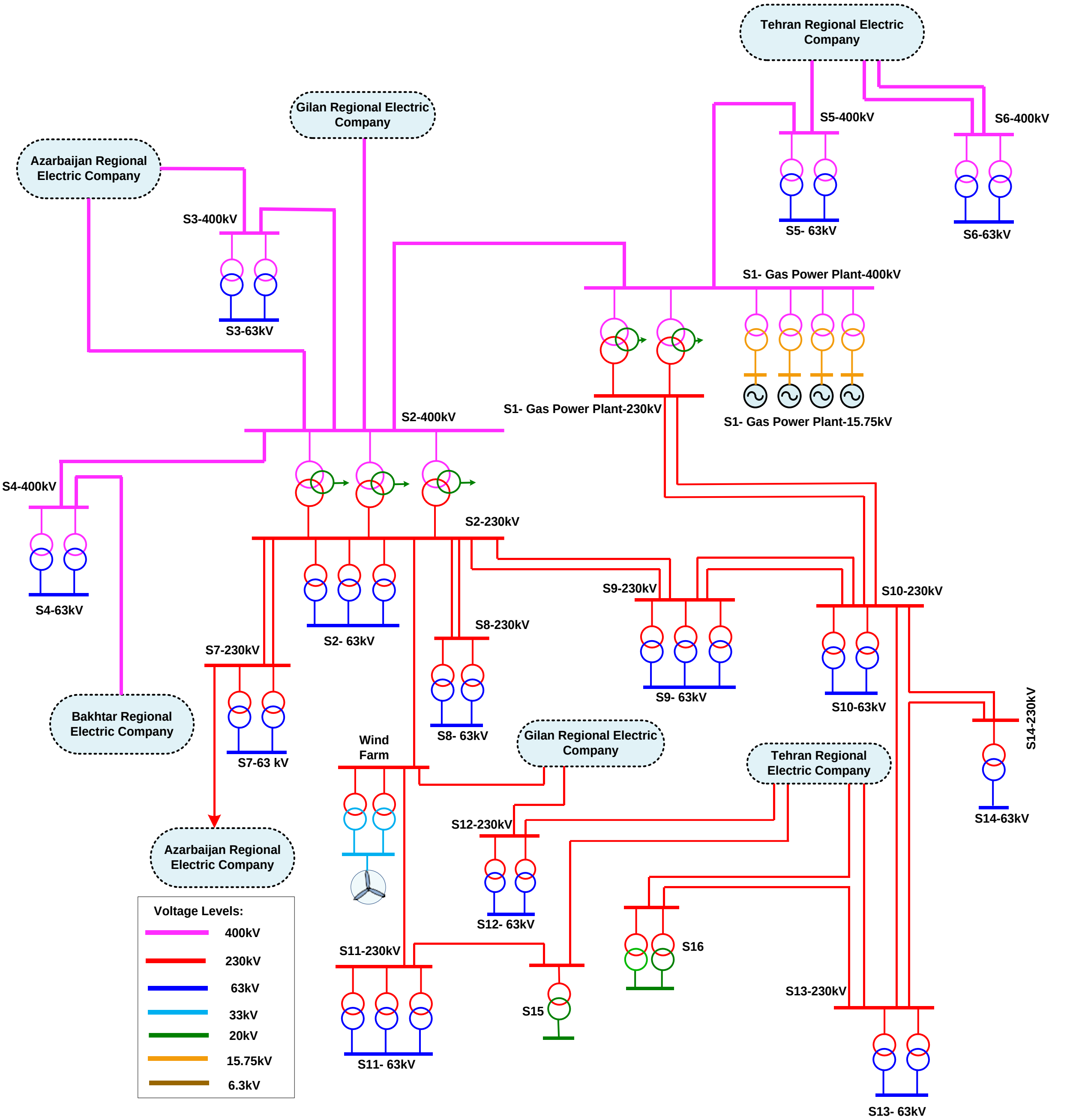

Fig. 8. Single-line diagram of ZREC network, part 1: EHV section

Table 8. The obtained results for the transformers when the objective function is power loss reduction

Substation No.	Sc.0		Sc.1			Sc.2		Sc.3		
	Tap Position	Loading (%)	Set point (Pu)	Tap Position	Loading (%)	Tap Position	Loading (%)	Set point (Pu)	Tap Position	Loading (%)
1	12	38.1	1.0036	12	37.2	12	37.7	1.007	12	35.5
2	14	72.6	0.9976	14	70.9	14	69.7	0.999	14	68.9
3	13	24.1	1.0502	14	24.8	13	27.5	1.0489	14	26.8
4	12	15.7	1.0341	13	15.7	12	15.7	1.0331	13	17.5
5	13	44.7	1.0495	14	46.5	13	45.2	1.0388	13	45.6
6	12	31.4	1.0478	13	32.2	12	30	1.0403	12	32.6
7	-4	39.1	1.0437	-4	37.5	-4	42.4	1.0452	-4	39.9
8	-3	38.4	1.0474	-4	38.2	-3	34.4	1.0433	-4	40
9	-5	44.4	1.034	-4	44.4	-5	37.9	1.0416	-4	38.5
10	-6	54.1	1.0272	-5	54	-6	53.6	1.0365	-5	48
11	16	39.8	1.0086	14	35.8	15	47.5	1.0147	14	44.5
12	-3	36	1.0356	-4	37.9	-4	33.5	1.0418	-5	38.5
13	16	38.6	1.0352	14	32.3	16	39.6	1.0359	15	35.7
14	-8	56.3	1.0522	-8	56.1	-8	57	1.0389	-7	55.7
15	17	62.8	1.0547	18	62	15	38	0.9877	13	31.5

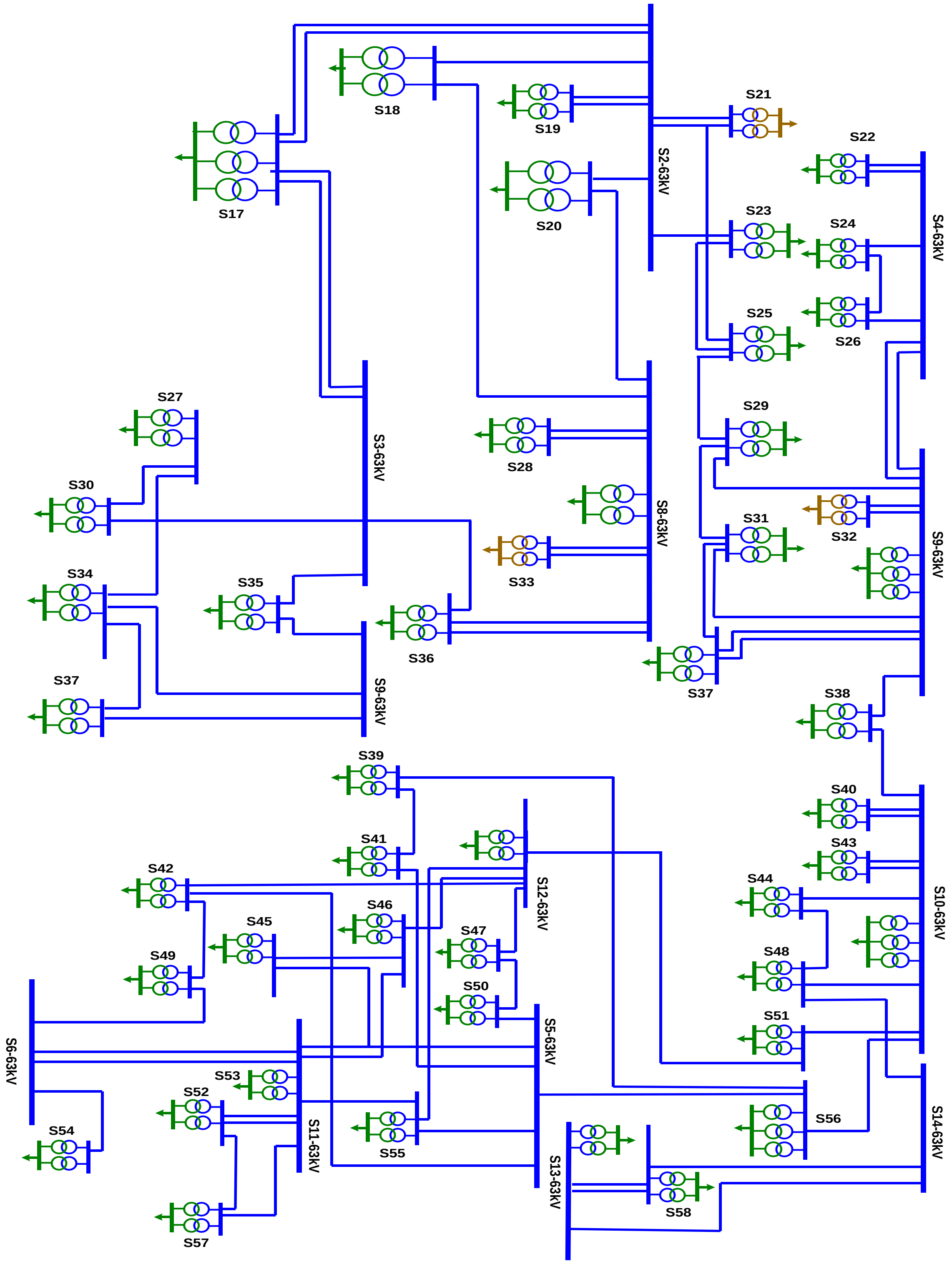

Fig. 9. Single-line diagram of ZREC network, part 2: HV and MV section

which the tap positions are not optimized, the voltage set-points of all transformers have been set to the real voltages of peak condition (occurred on 31 Jun 2020 at 12:58 p.m.). The real values of voltages on peak load condition have been recorded by the measuring devices in the substations. In scenarios 1 and 3, where the set-point of EHV/HV transformers are to be optimized, the set-points of HV/MV transformers have been adjusted to the real voltages of peak condition. In all scenarios, the loading limit is 80% and the voltage bound is [0.95, 1.05] p.u. Voltage regulation of each tap step in the power transformers is 1.67%.

The obtained results for all scenarios have been reported in Tables 7-9 as well as Fig. 10. Table 7 shows the values of different components of objective function in the considered scenarios. Table 8 gives the results obtained for power transformers settings. The switching status of candidate lines is also presented in Table 9 for all scenarios. According to Table 6, the power loss in the base scenario is 50.51MW, and it has been decreased to 49.93MW, 48.44MW, and 48.34MW in scenarios 1, 2, and 3, respectively. This shows that the minimum power loss is obtained in the third scenario (Tap+ reconfiguration). As it is aforementioned, power loss reduction is very important for the network operators. The value (worth) of power loss reduction (cost savings due to power loss reduction) in Iran was 3393.1 €/kW in 2019. In the third scenario, the power loss reduction compared to the base scenario is 2.17MW. This means that by the optimal operational planning in ZREC network, we would have a cost saving of 2.17MW×1000×3393.1€/MW= €7,363,027. In other words, by a proper tap adjustment and transmission switching, we would save about M€7.36.

Table 9. Lines switching results when the objective function is power loss reduction

Line No.	Line status (0: out ; 1:in)				Line No.	Line status (0: out ; 1:in)			
	Sc.0	Sc.1	Sc.2	Sc.3		Sc.0	Sc.1	Sc.2	Sc.3
1	1	1	1	1	41	1	1	1	1
2	1	1	1	1	42	1	1	1	1
3	1	1	1	1	43	1	1	1	0
4	0	0	1	0	44	1	1	1	1
5	1	1	1	1	45	1	1	1	1
6	1	1	1	1	46	0	0	1	1
7	1	1	1	1	47	1	1	1	1
8	0	0	1	1	48	1	1	1	1
9	0	0	1	1	49	1	1	0	1
10	1	1	1	1	50	1	1	1	0
11	1	1	1	0	51	1	1	1	1
12	1	1	1	1	52	0	0	1	1
13	0	0	0	1	53	1	1	1	1
14	1	1	0	0	54	0	0	0	1
15	1	1	1	1	55	1	1	1	1
16	1	1	1	1	56	0	0	1	1
17	1	1	1	1	57	0	0	1	0
18	1	1	1	1	58	1	1	1	0
19	0	0	1	0	59	1	1	1	1
20	1	1	1	1	60	1	1	1	1
21	1	1	1	1	61	1	1	1	1
22	1	1	1	1	62	1	1	1	0
23	0	0	1	1	63	0	0	1	1
24	1	1	0	0	64	1	1	1	0
25	1	1	1	1	65	1	1	1	1
26	1	1	1	1	66	1	1	1	1
27	1	1	1	1	67	1	1	1	1
28	0	0	0	1	68	1	1	1	1
29	0	0	1	0	69	1	1	1	1
30	1	1	1	1	70	1	1	1	1
31	0	0	1	1	71	1	1	1	1
32	1	1	1	1	72	1	1	1	1
33	0	0	1	1	73	1	1	1	1
34	0	0	1	1	74	1	1	1	1
35	1	1	1	1	75	1	1	1	1
36	1	1	1	1	76	0	0	0	1
37	0	0	1	1	77	1	1	1	1
38	0	0	0	0	78	1	1	1	1
39	0	0	0	1	79	1	1	1	1
40	1	1	1	1	80	0	0	1	0

In addition, the third scenario has the minimum loading for the transformers. Although the lines loading has been increased in scenario 3, however, no violation is seen in the lines loading, and the lines loading penalty is zero. The results also show that the number of EHV and HV buses whose voltages are lower than the accept8able limit (0.95pu) is 11 in the base scenario, while it has been decreased to 2 in the third scenario. Accordingly, the voltage penalty has been decreased from 1.018pu in the base scenario to 0.0589pu in the third scenario. One may observe that the power losses in scenarios 2 and 3 are close; but it should be noted that the voltage violation in scenario 2 is 0.3101pu while it is 0.0589 in scenario 3. In other words, the third scenario has the minimum power loss along with the minimum voltage violation. The last column of Table 6 shows that the total objective function is decreased from scenario Sc. 0 to Sc. 3. The normalized values for the components of Table 6 are depicted in Fig. 10 for different scenarios.

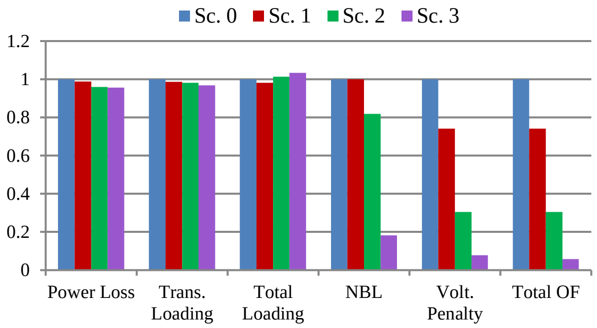

Fig 10. Normalized values of results in different scenarios

Regarding the execution time of the algorithm, it should be noted that this time is not the same in different scenarios. The execution time is short in scenario 1 (Tap Optimization) and large in scenario 3 (Tap+ Reconfiguration). In scenario 1, the execution time is about 1 minute, and it is about 5 minutes in scenario 3. This shows that the proposed approach has an acceptable execution time, and it can be employed in practical applications. Also, since the study is off-line and the system operator has no concern regarding these execution times.

5. CONCLUSION

Simultaneous transmission switching and OLTCs' tap adjustment is an effective tool that power system operators can employ for optimal operation of their networks. However, this coordination is a complicated optimization problem which is difficult to apply due to large number of decision variables and constraints to be handled. In this paper, the IPSO optimization algorithm was proposed in a DIgSILENT environment, which concurrently applies these two options for more optimal operation of practical power systems. The power system is modeled in DIgSILENT-Powerfactory environment to consider all the practical aspects of the problem. To eliminate the need for additional optimization software, an efficient IPSO algorithm has been implemented through DPL module of DIgSILENT. A real power system in Iran as well as the IEEE 14-bus test system are used to evaluate the performance of the developed approach in different scenarios. The results showed the efficiency of the proposed approach and verified that it can be practically employed by the electric utilities for optimal operation planning of real-case power systems. The proposed approach is a generic optimization model and can be applied to any other standard or real-world systems.

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