

A Mathematical Model for Minimizing Add-On Operational Cost in Electrical Power Systems Using Design of Experiments Approach

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ABSTRACT

One of the key functions of the Distribution System Operators (DSOs) of electrical power systems (EPS) is to minimize the transmission and distribution power losses and consequently the operational cost. This objective can be reached by operating the system in an optimal mode which is performed by adjusting control parameters such as on-load tap changer (OLTC) settings of transformers, generator excitation levels, and VAR compensators switching. The deviation from operation optimality will result in additional losses and additional operational cost of the power system. Reduction of the operational cost increases the power system efficiency and provides a significant reduction in total energy consumption. This paper proposes a mathematical model for minimizing the additional (add-on) costs based on Design of Experiments (DOE). The relation between add-on operational costs and OLTC settings is established by means of regression statistical analysis. The developed model is applied to a 20-bus test network. The regression curve fitting procedure requires simulation experiments which have been carried out by the DigSilent PowerFactory 13.2 Program for performing network power flow. The results show the effectiveness of the model. The research work raises the importance of the power system operation management of the EPS where the Distribution System Operator can avoid the add-on operational costs by continuous correction to get an operation mode close to optimality.

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1. INTRODUCTION

Technical power losses caused mainly by the resistance of EPS components include losses in the transmission, subtransmission, distribution system components, and in the connection links from distribution to consumers. Transmission and Distribution losses in the developed countries are in range from 4-12% [1, 2], while losses may increase to over 30% in other countries. Technical losses are possible to compute and control, provided the data of the concerned power system including load profile is available.

The value of power losses is one of the key indicators for quality of EPS operation. Operators of power systems make certain that the system is operating in or close to an optimal mode, so that the quality and reliability of supply to consumers are ensured. From the viewpoint of customers, the EPS should deliver electrical energy with high power quality in terms of voltage and frequency, high reliability, and minimal cost [3, 4, 5, 6]. Moreover, the green house emissions of the generation system should be reduced according to international regulations [7].

Any variations in the power system configuration or in the load profile alongside the nonsymmetry and nonlinearities of EPS can cause deviation from the ideal optimal mode. This deviation results in add-on power losses and consequently additional operational cost of supplied electrical energy. To enhance this situation, the load bus voltages should be maintained within specified limits. This goal can be achieved by a set of actions such as controlling generators excitation, switching reactive power compensators, and adjusting on load line tap changer (OLTC) of grid transformers [8, 9, 10, 11].

This paper focuses on minimizing the add-on power losses and operational costs by adjusting the OLTC of grid transformers. The basis of the study methodology is the Design of Experiments (DOE) approach which helps to detect the impact of inputs-factors on the output-response while realizing the objectives. This statistical theory found its applications in many areas including EPSs [12].

2. POWER LOSSES VERSUS CONTROL FACTORS

To obtain the power losses ΔP as a function of control parameters (for example OLTC setting of transformer i whose value corresponds to its turns ratio K_i), let us assume that the load profile of a power system is changed from m -variant to $(m+1)$ variant with optimal losses $\Delta P_{opt}^{(m)}$ corresponding to $K_{i_{opt}}^{(m)}$, and $\Delta P_{opt}^{(m+1)}$ corresponding to $K_{i_{opt}}^{(m+1)}$, respectively. If the control parameters of the second mode $(m+1)$ has some value $K_i^{(m+1)}$ which is not the optimal factor, the losses would be $\Delta P^{(m+1)}$ leading to additional losses $\delta P_{add}^{(m+1)}$ as follows:

$$\delta P_{add}^{(m+1)} = \Delta P^{(m+1)} - \Delta P_{opt}^{(m+1)} = f(K_i^{(m+1)} - K_{i_{opt}}^{(m+1)}) \quad (1)$$

In general equation (1) can be written as

$$\delta P_{add i} = f(K_i) \quad (2)$$

and, in terms of add-on operational cost, as:

$$C_{add i}^{(m+1)} = \delta P_{add i}^{(m+1)} T_{(m+1)} * B \quad (3)$$

where,

- $\delta P_{add i}^{(m+1)}$ actual add-on power losses for $(m+1)$ -mode for transformer i
- $T_{(m+1)}$ time duration of $(m+1)$ load mode defined by the daily load profile
- B cost of energy [USD/kWh]

From the above-mentioned equations, we can observe a relationship between add-on operational cost C_{add} and the switching-steps number of each transformer n_i . This relation can be predicted by use of linear regression procedure based on data acquired from designed experiments.

3. STATISTICALLY-DESIGNED EXPERIMENTS AND REGRESSION

Experimental design is a statistical theory that addresses the design and analysis of experiments. In an experimental study, one or more factors (independent variables) are changed so that the factors influence another variable referred to as the (response variable), or simply the response is obtained. The data obtained by conducting the experiments is analyzed by regression. Regression analysis serves to identify the relationship between a dependent variable (response) and one or more independent variables (factors). A linear or nonlinear regression model of the relationship is hypothesized, and the regression coefficients are calculated using the experimental data and the least-square method to develop an estimated regression equation. Experimental data are then employed to determine if the model is satisfactory. If the model is found to be satisfactory, the estimated regression equation can be used to predict the value of the dependent variable's given values for the independent variables [13].

The polynomial regression model

$$y_k = a_0 + a_1 x_k + a_2 x_k^2 + \dots + a_f x_k^f + \varepsilon_k \quad (k = 1, 2, \dots, N) \quad (4)$$

can be expressed in matrix form in terms of a design matrix \mathbf{X} , a response vector \vec{y} , a parameter vector \vec{a} , and a vector $\vec{\epsilon}$ of random errors. The i^{th} row of \mathbf{X} and \vec{y} will contain the x and y values for the i^{th} data sample. Then the model can be written as a system of linear equations [12, 15, 16]:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} 1 & x_1 & x_1^2 & \dots & x_1^f \\ 1 & x_2 & x_2^2 & \dots & x_2^f \\ 1 & x_3 & x_3^2 & \dots & x_3^f \\ \vdots & \vdots & \vdots & \dots & \vdots \\ 1 & x_n & x_n^2 & \dots & x_n^f \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ a_f \end{bmatrix} + \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \vdots \\ \epsilon_n \end{bmatrix} \quad (5)$$

which when using pure matrix notation is written as

$$\vec{y} = \mathbf{X}\vec{a} + \vec{\epsilon} \quad (6)$$

The vector of estimated polynomial regression coefficients (using ordinary least-squares method) is:

$$\hat{\vec{a}} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\vec{y} \quad (7)$$

The final regression model fitting the experimental data is:

$$\hat{y} = \hat{\vec{a}}\mathbf{X} = \mathbf{X}(\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{y} \quad (8)$$

Equation (2) that shows add-on loss δP_{addi} as a function of \mathbf{K}_i can be considered as a relation between add-on loss and switching step number of OLTC setting n_i which can be determined as:

$$n_i = \left| \frac{K_{io}^{(m)} - K_{io}^{(m+1)}}{K_{step\ i}} \right| \quad (9)$$

where, $K_{step\ i}$ is position step of OLTC of transformer i . With a suitable scaling of the vertical axis, Equation (2) can be written as $C_{addi} = f(\mathbf{K}_i)$. The values of additional operational cost can be computed by running a power flow software for the EPS with various load modes and designed experiments concerning the sets of OLTC of transformers.

To apply a regression analysis, a regression model should first be selected. Regression models estimate y values for known x values. The second order polynomial regression model is selected as:

$$\hat{y}_k = a_0 + a_1x_k + a_2x_k^2 \quad (10)$$

Using the least squares method, the normal equations are formulated as:

$$\begin{bmatrix} N & \sum_{k=1}^N x_k & \sum_{k=1}^N x_k^2 \\ \sum_{k=1}^N x_k & \sum_{k=1}^N x_k^2 & \sum_{k=1}^N x_k^3 \\ \sum_{k=1}^N x_k^2 & \sum_{k=1}^N x_k^3 & \sum_{k=1}^N x_k^4 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \sum_{k=1}^N y_k \\ \sum_{k=1}^N x_k y_k \\ \sum_{k=1}^N x_k^2 y_k \end{bmatrix} \quad (11)$$

These normal equations have unique solutions provided that x_k is distinct.

The curve fitting can be performed by Matlab using the toolbox **cftool** (**xdata**, **ydata**) which opens Curve Fitting Tool with data, factors **xdata** and **ydata**. **xdata** and **ydata** must be vectors of the same size. The results include values of constants a 's and the indicators of goodness of fit: **SSE**, **R²**, adjusted **R²** and **RMSE**.

The regression model in terms of factors and response of transformer i is represented as:

$$\hat{C}_{add,ik} = a_0 + a_1 n_{ik} + a_2 n_{ik}^2 \tag{12}$$

where $\hat{C}_{add,ik}$ and n_{ik} represent \hat{y}_k and x_k , respectively.

4. CASE STUDY

4.1 Test Network

The electrical network used in this study is given in Figure 1. It consists of 20 buses, 20 branches and 10 transformers, 5 of which are equipped with OLTCs.

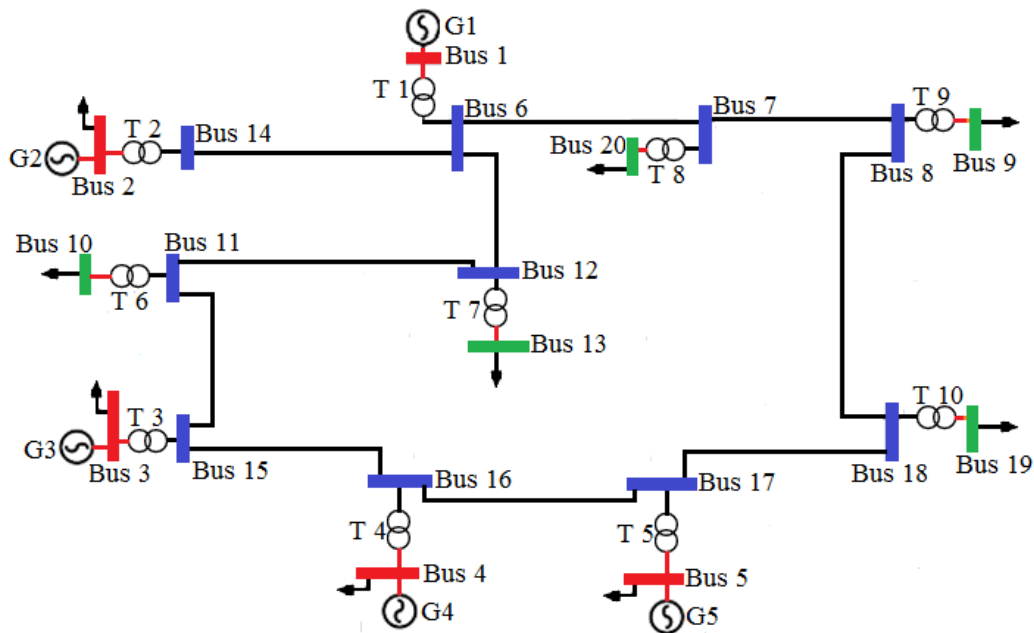


Figure 1. Single Line diagram of the test network

The input data are summarized in Tables 1, 2 and 3.

Table 1. Data of the 20-bus test network

Bus No.	PL (MW)	PG (MW)	Bus No.	PL (MW)	PG (MW)
1	0.00	0.00	11	0.00	0.00
2	40.00	100.00	12	0.00	0.00
3	45.00	100.00	13	40.00	18.60
4	40.20	100.00	14	0.00	0.00
5	30.00	100.00	15	0.00	0.00
6	0.00	0.00	16	0.00	0.00
7	0.00	0.00	17	0.00	0.00
8	0.00	0.00	18	0.00	0.00
9	36.20	16.50	19	70.00	26.60
10	63.80	28.80	20	65.00	28.20

Table 2. Branches data of test network

Branch No.	From Bus	To Bus	Series Impedance (p.u)		Tap Setting	MVA Rating
			R	X		
1.	1	6	0.00000	0.13000	-	500.00
2.	2	14	0.00000	0.11000	-	500.00
3.	3	15	0.00000	0.11000	-	500.00
4.	4	16	0.00000	0.11000	-	500.00
5.	5	17	0.00000	0.11000	-	500.00
6.	6	7	0.05700	0.17370	-	150.00
7.	6	12	0.04158	0.16144	-	150.00
8.	6	14	0.05300	0.12700	-	150.00
9.	7	8	0.03018	0.09196	-	150.00
10.	7	20	0.00000	0.12600	1.0681	100.00
11.	8	9	0.00000	0.12000	1.0681	80.00
12.	8	18	0.05091	0.15326	-	150.00
13.	11	10	0.00000	0.12600	1.0681	80.00
14.	11	12	0.06173	0.18596	-	150.00
15.	11	15	0.02079	0.06335	-	150.00
16.	12	13	0.00000	0.10740	1.0681	63.00
17.	15	16	0.02884	0.08787	-	150.00
18.	16	17	0.07376	0.22479	-	150.00
19.	17	18	0.06639	0.20231	-	150.00
20.	18	19	0.00000	0.12600	1.0681	100.00

Table 3. Data of the transformers and modes losses

Transformer No	1	2	3	4	5	6	7	8	9	10
$K_{step i}$	-	-	-	-	-	0.0788	0.0788	0.0788	0.0788	0.0788
$K_{step 0}$	0.1515	0.1515	0.1136	0.1136	0.1136	4.000	4.000	4.000	4.000	4.000
$K_{step 1}$	-	-	-	-	-	4.0788	4.0788	4.0788	4.0788	4.0788
$K_{step 2}$	-	-	-	-	-	4.1576	4.1576	4.1576	4.1576	4.1576
$K_{step 3}$	-	-	-	-	-	4.2364	4.2364	4.2364	4.2364	4.2364
$K_{step 4}$	-	-	-	-	-	4.3152	4.3152	4.3152	4.3152	4.3152
$K_{step 5}$	-	-	-	-	-	4.3949	4.3949	4.3949	4.3949	4.3949
Mode 1 (Optimal)										
$K_{optimal}$	0.1515	0.1515	0.1136	0.1136	0.1136	4.3949	4.3949	4.0000	4.0000	4.0000
ΔP_0 ; MW						19.565				
Mode 2 (Peak)										
D_i	0.1515	0.1515	0.1136	0.1136	0.1136	4.0000	4.0000	4.2364	4.0000	4.0000
ΔP ; MW						31.68				
OLTC: n'_i	-	-	-	-	-	5	5	5	5	5

Figure 2 shows Load Mode (m)–optimal and ($m+1$)- peak) power losses in MW, without proper tapping of the 5 transformers .

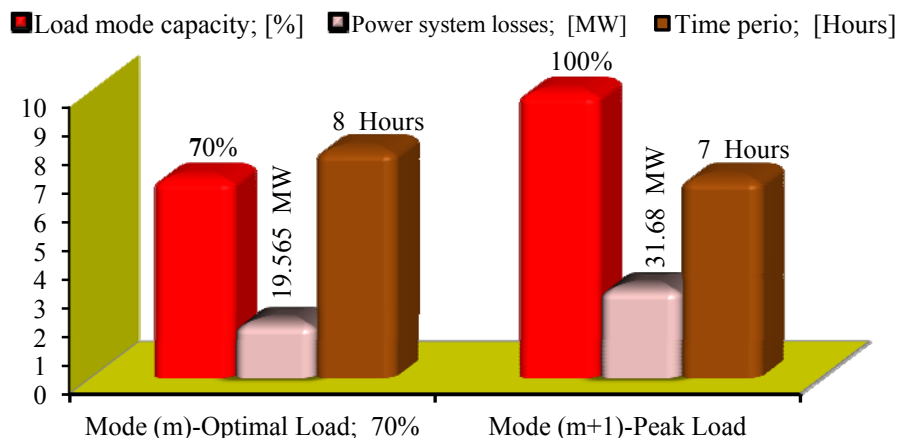


Figure 2. Power Losses of modes m and ($m+1$) Load varents

The 5 single-factor test scenarios are shown in Table 4, from which the fitted regression curves are obtained by Matlab.

Table 4. Single-Factor Test Scenario for Load Mode (*m+I*)

Scenarios	T6 TC setting	T7 TC setting	T8 TC setting	T9 TC setting	T10 TC setting	ΔP MW	δP MW
1	1	0	0	0	0	38.24	6.56
2	2	0	0	0	0	35.46	3.78
3	3	0	0	0	0	34.77	3.09
4	4	0	0	0	0	34.08	2.40
5	5	0	0	0	0	33.53	1.85
6	0	1	0	0	0	39.86	8.18
7	0	2	0	0	0	39.66	7.98
8	0	3	0	0	0	39.57	7.89
9	0	4	0	0	0	39.42	7.74
10	0	5	0	0	0	39.21	7.53
11	0	0	1	0	0	36.70	5.02
12	0	0	2	0	0	34.49	2.81
13	0	0	3	0	0	33.82	2.14
14	0	0	4	0	0	33.44	1.76
15	0	0	5	0	0	32.44	0.759
16	0	0	0	1	0	39.68	8.00
17	0	0	0	2	0	38.15	6.471
18	0	0	0	3	0	36.12	4.439
19	0	0	0	4	0	35.894	4.214
20	0	0	0	5	0	34.63	2.95
21	0	0	0	0	1	39.66	7.98
22	0	0	0	0	2	39.16	7.48
23	0	0	0	0	3	39.17	7.49
24	0	0	0	0	4	39.18	7.50
25	0	0	0	0	5	39.21	7.53

From Figure 3 it is obvious that the transformers 7 and 10 have negligible effects on add-on operational costs, while the transformers 6, 8, and 9 are considered as critical components. Therefore, we check the multifactor scenarios of transformers 6, 8 and 9. The number of these scenarios should be $2^3 = 8$. The power flow for these scenarios result in values of power losses and add-on costs as shown in Table 5.

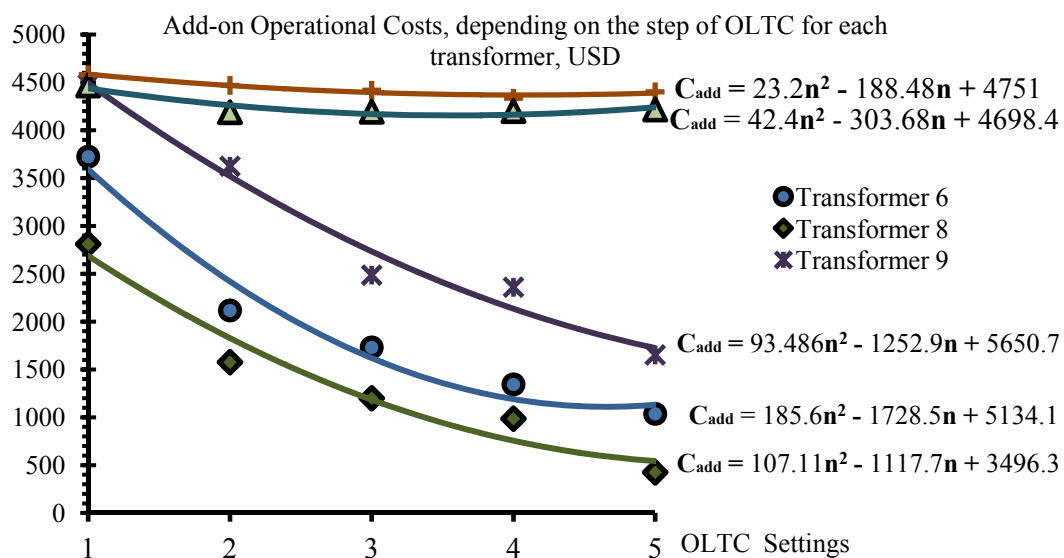


Figure 3. Fitted regression curves of the 5 single-factor test scenarios

Table 5. Multifactor Test Scenarios for Load Mode ($m+1$)

Scenarios No;	T6	T8	T9	ΔP ; MW	δP ; MW
1	-	-	-	44.425	12.745
2	+	-	-	35.054	1.107
3	-	+	-	38.444	6.764
4	-	-	+	39.65	7.97
5	-	+	+	37.85	6.17
6	+	+	+	31.73	0.05
7	+	+	-	32.207	0.527
8	+	-	+	34.536	2.856

Figure 4 shows Load flow results of power losses and add-on power losses of Multifactor Experiments for Load Mode ($m+1$) load.

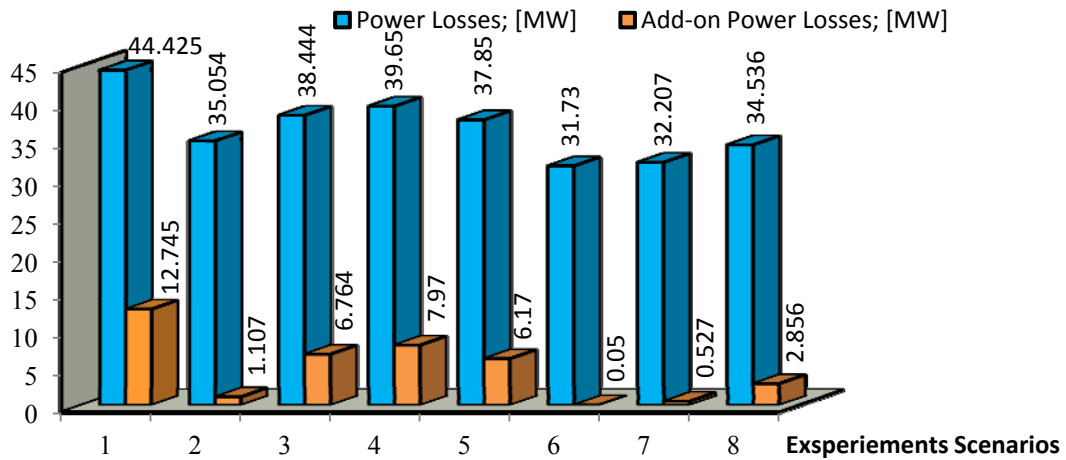


Figure 4. Load flow results of power losses and add-on power losses of Multifactor Experiments for Load Mode ($m+1$)

The graphical chart of add-on operational losses and add-on operational costs of multi-factor test scenarios for Load Mode ($m+1$) is shown in Figure 5.

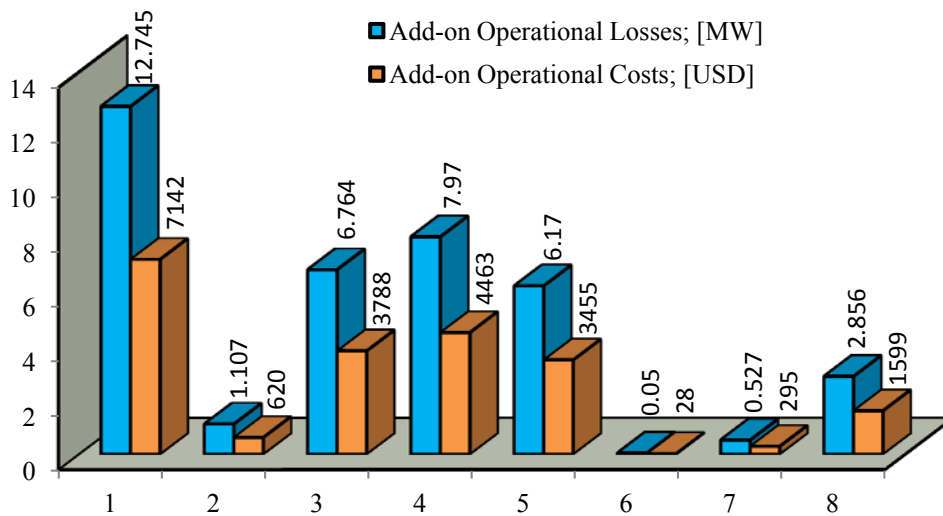


Figure 5. Add-on operational losses and add-on operational costs of multi-factor test scenarios for Load Mode ($m+1$)

From Figure 5 it is obvious that the scenario 6 gives the minimum additional power losses of 0.05 MW and consequently the lowest add-on operational cost. This scenario dictates that the OLTC settings of all three transformers should be at the high position (Step 5).

5. CONCLUSIONS

The paper presents a mathematical model and an algorithm of minimizing the add-on operational real power losses and add-on operational cost in electrical power systems, based on Design of Experiments approach and polynomial linear regression. The model takes into consideration the control parameters of OLTC transformers. However, it can easily be extended to consider other control variables such as generator excitation levels, and VAR compensators switching. The developed model and algorithm should be beneficial for Distribution System Operator in detecting critical transformers and meeting proper tapping to minimize the power system add-on losses. The model has been successfully applied to a test network and the results obtained were examined and discussed.

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