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Comprehensive Power Losses Model for Electronic Power Transformer

QUANYOU YUE[1], CANBING LI[1], (Senior Member, IEEE), YIJIA CAO[1], (Senior Member, IEEE), YUQING HE[1], BINGLIN CAI[1], QIUWEI WU[2], (Senior Member, IEEE), AND BIN ZHOU[1], (Senior Member, IEEE)

[1]Hunan Key Laboratory of Intelligent Information Analysis and Integrated Optimization for Energy Internet, College of Electrical and Information Engineering, Hunan University, Changsha 410082, China

[2]Center for Electric Power and Energy, Department of Electrical Engineering, Technical University of Denmark, DK 2800 Kongens Lyngby, Denmark

Corresponding author: Canbing Li (licanbing@qq.com)

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ABSTRACT The electronic power transformer (EPT) has higher power losses than the conventional transformer. However, the EPT can correct the power factor, compensate the unbalanced current, and reduce the line power losses in the distribution network. Therefore, the higher power losses of the EPT and the consequent reduced power losses in the distribution network require a comprehensive consideration when comparing the power losses of the EPT and conventional transformer. In this paper, a comprehensive power losses analysis model for the EPT in distribution networks is proposed. By analyzing the EPT self-losses and considering the impact of the nonunity power factor and the three-phase unbalanced current, the overall power losses in the distribution network when using the EPT to replace the conventional transformer is analyzed, and the conditions in which the application of the EPT can cause less power losses are obtained. Based on this, the sensitivity analysis for the EPT comprehensive power losses model is carried out by comparing the value of each parameter variation impact on the EPT losses model. In the case study, the validity of the comprehensive power losses model is verified.

INDEX TERMS Comprehensive power losses model, electronic power transformer, distribution network, power factor, unbalanced current.

I. INTRODUCTION

The electronic power transformer (EPT), also called solid-state transformer (SST) [1], [2], has been regarded as one of the 10 most emerging technologies by Massachusetts Institute of Technology (MIT) Technology Review in 2010 [3]. In 1970, the earliest concept of the EPT was proposed in [4], where the EPT was a high frequency AC / AC converter circuit model. In 1999, the power electronic transformer for high-voltage and high-power applications was proposed in [5], and then significant progress was made in the following years [6]–[8]. With the development of high-power converters, the EPT has been extensively investigated for the distribution systems [8]–[10] and other power fields [8], [11]. However, the high power losses and high cost [3] are restricting its widespread applications.

The U.S. Department of Energy released a standard for liquid and dry type distribution transformers in October 2007 [12], which requires the efficiency of the dry transformer should be higher than 97%, and the efficiency of the oil-immersed transformer is close to 99.5%. Standardization Administration of the People's Republic of China also released the latest three-phase distribution transformers' energy efficiency standard on September 11, 2015 [13], [14], which requires 3-class dry distribution transformer's minimum efficiency should not be less than 96.8%. The EPT has a power converter based on cascading configuration, and the maximum efficiency of each level is about 97%-98% [3], [15], [16]. In [17], a power losses comparison of six representative topologies for the implementation of the EPT was performed, and the efficiency of the EPT based on the most widely used topology which is comprised of multilevel rectifiers, full bridge and inverters is only 91.185%. The maximum efficiency of the EPT in operation, which was the fundamental component of the innovative smart micro-grid future renewable electric energy delivery and management (FREEDM) proposed by the North Carolina State University, was only 94% [18], [19]. Therefore, compared to the conventional transformer, the EPT has a lower efficiency, which is the main issue that restricts its large-scale application in the distribution network.

However, the EPT can provide not only the basic functions of the conventional transformer such as voltage transformation, isolation and power transmission, but also many additional functions such as: automatic voltage regulation, power factor correction, power flow control, fault current limitation and three-phase unbalanced current compensation [20], [21], etc. Among these additional functions, the power factor correction and three-phase unbalanced current compensation can effectively reduce the additional power losses in distribution networks. First, the EPT can correct the power factor at the input side to independently adjust the power factor of the distribution network [22], which ensures the distribution network remains at unity power factor operation. As such, the voltage drop on distribution lines can be compensated and the active transmission lines losses can be reduced. Then, when the unbalanced current occurs, the EPT can maintain the balance of the three-phase current in power grids by injecting negative sequence current into the distribution network, which can reduce the power losses on phase lines and neutral lines.

Rural power grids have the characteristics of load dispersion and long distribution distance lines [23], [24], where the low power factor and the proliferation of single-phase loads widely exist. The same phenomenon can be found in industrial and enterprise distribution networks with long distribution lines [25]–[27], where there are heavy single-phase or single-phase and three-phase mixed loads, such as lighting loads. Besides, single-phase traction and electric transit or railroad systems can also cause the low power factor and unbalanced current in the utility three-phase system [28]–[30]. When the EPT is applied to these distribution networks, it can reduce the line power losses through the power factor correction and three-phase unbalanced current compensation. Therefore, in general, the power losses of the EPT are higher than the losses of the conventional transformer. However, in specific operating conditions, if the EPT versatile functions can be considered, the application of the EPT may decrease the overall power losses.

In this paper, a comprehensive power losses model for the EPT in the distribution network is proposed. The reduced losses on the distribution lines caused by using the EPT are analyzed in the case of non-unity power factor and three-phase unbalanced current. Taking into account the losses of the EPT and conventional transformer, the conditions that the power factor and the current unbalanced degree should satisfy when using the EPT to replace the conventional transformer can cause less power losses are identified. Based on this, the impact of each parameter variation is obtained by the sensitivity analysis. In case study, the effectiveness of the model is verified.

This paper is organized as follows. Section II analyzes the EPT self-losses. Section III analyzes the reduced power losses in distribution networks with the application of the EPT. The comprehensive power losses model for EPT is established and its sensitivity analysis is conducted in Section IV. A case study simulation is carried out in Section V. Finally, we summarize this paper in Section VI.

II. LOSSES MODEL FOR ELECTRONIC POWER TRANSFORMER

A. POWER LOSSES IN EPT POWER CONVERTERS

The EPT power converters include voltage source converters (VSC) and H-bridge converters (DC-DC converter) [31]. In this paper, the losses model of AC-DC-AC EPT is established. the VSC is located at the input and output of the EPT with the functions of AC-DC and DC-AC conversion. H-bridge converters have the functions of DC-DC transmission and voltage conversion. Power losses on the rectifier side and inverter side of the VSC are analyzed as follows.

When the converter switch is on-state, the Insulated Gate Bipolar Transistor (IGBT) module collector-emitter saturation voltage u_{CE} and collector current i_C in the EPT can be expressed as,

$$u_{CE} = U_{CE0} + R_T \times i_c \tag{1}$$

where U_{CE0} is the IGBT no load voltage, and R_T is the IGBT on-state resistance.

The value of U_{CE0} and R_T can be calculated using the datasheet of device characteristics provided by manufacturing companies as shown in Fig 1.

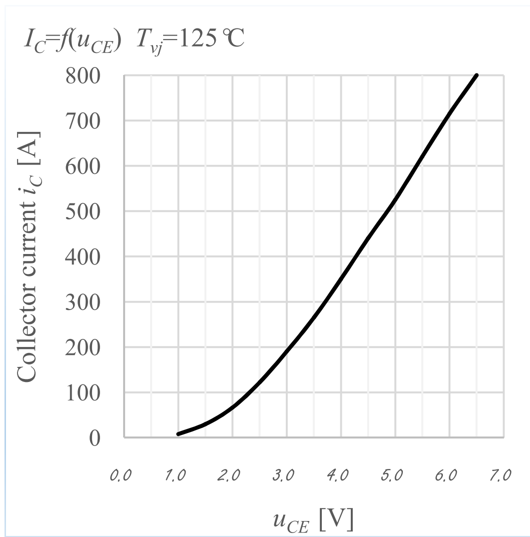


FIGURE 1. IGBT module output characteristic curve.

When the EPT works in the unity power factor mode, the phase current i_a and voltage u_a are,

$$\begin{aligned} i_a(t) &= I_m \sin \omega t \\ u_a(t) &= U_m \sin \omega t \end{aligned} \tag{2}$$

where I_m and U_m are the amplitude of phase voltage and phase current, respectively.

The duty cycle d_T and d_D in the IGBT and freewheeling diode are,

$$d_T = \frac{1}{2}(1 + M \sin\omega t)$$
$$d_D = 1 - d_T = \frac{1}{2}(1 - M \sin\omega t) \quad (3)$$

where M is the modulation degree, ranging from 0-1.

Then the current flowing through the IGBT and freewheeling diode can be calculated as follows,

$$\begin{aligned} I_{T.av} &= \frac{1}{2\pi}\int_0^{\pi} d_T i_a d\omega t = I_m\left(\frac{1}{2\pi} + \frac{M}{8}\right) \\ I_{T.rms}^2 &= \frac{1}{2\pi}\int_0^{\pi} d_T i_a^2 d\omega t = I_m^2\left(\frac{1}{8} + \frac{M}{3\pi}\right) \\ I_{D.av} &= \frac{1}{2\pi}\int_0^{\pi} d_D i_a d\omega t = I_m\left(\frac{1}{2\pi} - \frac{M}{8}\right) \\ I_{D.rms}^2 &= \frac{1}{2\pi}\int_0^{\pi} d_D i_a^2 d\omega t = I_m^2\left(\frac{1}{8} - \frac{M}{3\pi}\right) \end{aligned} \quad (4)$$

where $I_{T.av}$ and $I_{D.av}$ are the average current, respectively. $I_{T.rms}^2$ and $I_{D.rms}^2$ are the root-mean-square current in the IGBT and freewheeling diode, respectively.

Based on (1) and (4), the conduction losses in the IGBT P_{Tcon} can be expressed as,

$$\begin{aligned} P_{Tcon} &= \frac{1}{T}\int_0^{T}(u_{CE} \times i_c)d\omega t = U_{CE0}I_{T.av} + R_T I_{T.rms}^2 \\ &= \left(\frac{U_{CE0} \times I_m}{2\pi} + R_T\frac{I_m^2}{8}\right) + M\left(U_{CE0}\frac{I_m}{8} + R_T\frac{I_C^2}{3\pi}\right) \end{aligned} \quad (5)$$

Similarly, the conduction losses in the freewheeling diode P_{Dcon} can be expressed as,

$$P_{Dcon} = \frac{U_{D0}I_m}{2\pi} + \frac{R_D I_m^2}{8} - M\left(\frac{U_{D0}I_m}{8} + \frac{R_D I_m^2}{3\pi}\right) \quad (6)$$

where U_{D0} is the freewheeling diode no load voltage and R_D is the freewheeling diode on-state resistance.

The switching losses in the IGBT module can be fitted by the switching losses and the collector current characteristic curve shown in Fig. 2. By curves matching, the turn-on energy losses E_{on} and the turn-off energy losses E_{off} can be expressed as,

$$\begin{aligned} E_{on} &= k_1 i_c + k_2 \\ E_{off} &= k_3 i_c \end{aligned} \quad (7)$$

where k_1, k_2 and k_3 are constants.

Then, the average switching losses P_S in the IGBT can be calculated as,

$$\begin{aligned} P_S &= \frac{f_s}{2\pi}\int_0^{\pi}((k_1 + k_3)i_C + k_2)\frac{u_C}{U_R}\mathrm{d}\omega t \\ &= \frac{fU_m I_m(k_1 + k_3)}{4U_R} + \frac{fU_m k_2}{\pi U_R} \end{aligned} \quad (8)$$

where U_R is the rated voltage of the IGBT module, and f is the effective switching frequency of the IGBT module in the EPT.

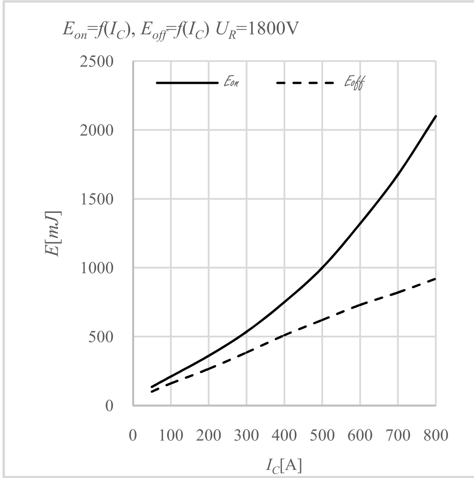


FIGURE 2. IGBT module switching losses characteristic curve.

Similarly, the switching losses in the freewheeling diode P_{rec} can be calculated as,

$$P_{rec} = \frac{fU_m I_m k_4}{4U_R} + \frac{fU_m k_5}{\pi U_R} \quad (9)$$

where k_4 and k_5 are constants, which can be obtained by the fitting curve of the diode recovery losses.

Similarly, the power losses in the H-bridge converter can be analyzed following the same steps. The waveform of the current flowing through the IGBT and freewheeling diode in the H-bridge converter is a square wave with a continuous ratio of 0.5, the amplitudes of the voltage and the current in the conduction process are constants, so the voltage drop u_{CE} in the conducting state is a constant value. And the conduction losses can be calculated as follows,

$$\begin{aligned} P_{Tcon} &= \frac{1}{2\pi}\int_0^{\pi} u_{CE} i_C d\omega t = u_{CE} I_{C.av} \\ P_{Dcon} &= \frac{1}{2\pi}\int u_D i_D d\omega t = u_D I_{D.av} \end{aligned} \quad (10)$$

where $I_{C.av}$ and $I_{D.av}$ are determined by the conduction time.

With a certain conduction current, switching losses in the IGBT are constants, which can be calculated as,

$$P_s = f((k_1 + k_3)i_C + k_2)\frac{u_{CE}}{U_R} \quad (11)$$

Similarly, the switching losses in the freewheeling diode are,

$$P_{rec} = f(k_4 i_C + k_5)\frac{U_D}{U_R} \quad (12)$$

B. POWER LOSSES IN EPT INTERMEDIATE FREQUENCY TRANSFORMER

The power losses of the intermediate frequency (IF) transformer in the EPT consist of core losses and winding losses [32]. The core losses P_C are mainly composed of hysteresis losses, eddy current losses and residual losses. Based on the improved Steinmetz equation [33], it can be calculated as,

$$P_C = P_V V = FKf^{\alpha}B^{\beta}V \quad (13)$$

where P_V is the core losses power density, V is the core effective volume in the IF transformer, f is the frequency of the square wave signal, and it is also the switching frequency in the H-bridge converter, B is the flux density in the core, K, α and β are constants, when the core material is made of ferrite, their value are 4.88×10^{-5}, 1.63 and 6.22, respectively. F is the flux waveform factor with a value of $\pi/4$ when the waveform of the current flowing through the IF transformer is a square wave.

The current square wave in the IF transformer can be decomposed into the current harmonic components by the Fourier decomposition,

$$i(t) = I_{dc} + \sum_{n=1}^{\infty} I_n \cos(n\omega t + \varphi_n) \tag{14}$$

where I_{dc} is the DC current component, I_n is the nth harmonic amplitude and φ_n is the phase angle.

The total winding losses P_W caused by the fundamental and harmonics current can be calculated as,

$$P_W = R_{dc}\left(I_{dc}^2 + \frac{1}{2}\sum_{n=1}^{\infty} I_n^2 F_{Rn}\right) \tag{15}$$

where R_{dc} is the winding DC resistance, I_n is the nth harmonic current root mean square and F_{Rn} is the AC/DC resistance ratio of the windings with the nth harmonic excitation. The exact value of the winding losses can be obtained by taking the fundamental wave, 3rd, 5th and 7th harmonics.

Based on the above analysis, the EPT losses model can be established by adding the EPT power converters losses and IF transformer losses.

III. EFFECT OF APPLYING EPT ON DISTRIBUTION NETWORK LOSSES

A. APPLYING EPT IN NON-UNITY POWER FACTOR CONDITION

The primary side of the EPT has a voltage-type Pulse-Width Modulation (PWM) rectifier circuit, which is one of the notable characteristics of the electronic power transformer [5]. Therefore, by using the voltage-current double close-loop control method, regardless of the load is inductive or capacitive, the input side of the EPT can adjust the load power factor independently. In such cases the distribution network can remain at unity power factor operation [33], [34]. In the meantime, in the low-voltage distribution networks, the EPT is close to the load, and the adjustable power factor is determined by the load. So, as the electrical power is transmitted through the EPT to the load, the EPT and load can be considered as a whole. The EPT can adjust the total power factor at 1 by absorbing or generating reactive power. In this setting, the reduced losses distribution is illustrated in Fig. 3. The reduced losses are not on the lines between the load and the EPT, but on the lines between the EPT and the distribution network or power supply, i.e., that is, the power losses on distribution lines are reduced. Therefore, it is necessary to analyze the overall distribution network power losses when

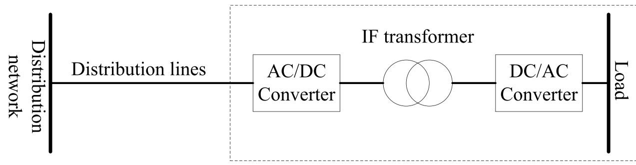


FIGURE 3. EPT equivalent circuit diagram in the distribution network.

using the EPT to replace the conventional transformer in the case of non-unity power factor.

When the conventional transformer transmits electric power, the power losses on the distribution lines P_l can be calculated as,

$$P_l = I^2 \times R = \frac{P^2 R}{U^2 \cos^2 \varphi} \times 10^{-3} \tag{16}$$

where R is the resistance of the distribution lines, $\cos\varphi$ is the total power factor of the transformer and the load, in addition to knowing the load power factor, the calculation of this parameter also requires the active power loss and reactive power loss of the conventional transformer.

The active power loss of the conventional transformer P_b consist of no-load loss P_0 and load loss P_N.

$$P_b = P_0 + P_N \tag{17}$$

where the no-load loss P_0 is measured at the rated voltage, which does not vary with the load. The short-circuit loss at rated current is the rated load loss P_{kN}, and the load loss is proportional to the square of the rated load loss, which is,

$$P_N = \beta^2 P_{kN} \tag{18}$$

where β is the transformer load rate. In general, the no-load loss and rated load loss can be obtained by the performance parameters list provided by the transformer manufacturer.

The reactive power loss of the conventional transformer Q_b can be expressed as,

$$Q_b = \left(\frac{I_0}{100}\right) \times S + \frac{U_k}{100} \times S \tag{19}$$

where S is the capacity of the transformer, I_0 is the load current percentage and U_k is the impedance voltage percentage.

Thus, the total power factor of the conventional transformer and the load can be calculated as,

$$\cos\varphi = \frac{S\cos\varphi_0 + P_b}{S + \sqrt{Q_b^2 + P_b^2}} \tag{20}$$

where $\cos\varphi_0$ is the power factor of the load.

Utilizing the EPT to replace the conventional transformer in the distribution network can adjust the total power factor at 1. Then the reduced losses on the lines ΔP_l can be expressed as,

$$\Delta P_l = \left(\frac{P}{U}\right)^2 \times R \times \left(\frac{1}{\cos^2\varphi} - 1\right) \tag{21}$$

From (20) and (21), it can be seen that the lower load power factor, the lower total power factor of the transformer and the load, and the higher losses reduction.

B. APPLYING EPT IN THREE-PHASE UNBALANCED CONDITION

Three-phase unbalance is very common in medium and low voltage distribution networks [35], especially in the remote rural areas, industrial and enterprise distribution networks or electric transit and railroad systems, which contain a large number of single-phase loads. The EPT can compensate the three-phase unbalanced current, and then reduce the additional losses on distribution lines. Therefore, applying the EPT in three-phase unbalanced conditions will affect the power losses in distribution networks.

The three-phase current unbalanced degree ε is defined as,

$$\varepsilon = \frac{I_2}{I_1} \times 100\% = \frac{\left|\frac{1}{3}\left(\dot{I}_a + \alpha^2 \dot{I}_b + \alpha \dot{I}_c\right)\right|}{\left|\frac{1}{3}\left(\dot{I}_a + \alpha \dot{I}_b + \alpha^2 \dot{I}_c\right)\right|} = \frac{\sqrt{\left(I_a^2 + I_b^2 + I_c^2 - I_a I_b - I_a I_c - I_b I_c\right)}}{3I_{av}} \tag{22}$$

where I_1 and I_2 are the root mean square of the positive sequence current component and the negative sequence current component, respectively. α is the phase transformation operator, $\alpha = e^{120^\circ}$, and I_{av} is the three-phase mean current.

When the phase resistance and neutral resistance in the three-phase four-wire system are all R, compared to the three-phase balance condition, the additional power losses on phase lines ΔP_p in the three-phase current unbalance condition can be expressed as,

$$\Delta P_P = \left(I_a^2 + I_b^2 + I_c^2\right) R - 3I_{av}^2 R = \frac{(I_a - I_b)^2 + (I_a - I_c)^2 + (I_b - I_c)^2}{3R} \tag{23}$$

And the neutral current I_N is,

$$I_N = I_a + I_b \alpha^2 + I_c \alpha \tag{24}$$

Therefore, the additional power losses on neutral lines ΔP_n can be calculated as follows,

$$\Delta P_n = I_N^2 R = \left(I_a^2 + I_b^2 + I_c^2 + I_a I_b + I_a I_c - I_b I_c\right) \times R \tag{25}$$

Based on the above analyses, the total reduced losses ΔP_t on distribution lines are,

$$\Delta P_t = \Delta P_n + \Delta P_p = \frac{6I^2\varepsilon^2}{R} + 3I^2 R\varepsilon^2 \tag{26}$$

From (22) and (26), it can be seen that no matter how the three-phase unbalanced current changes, a certain three-phase current unbalance degree corresponds to the fixed reduced losses. Therefore, regardless of how the value of the three-phase unbalanced current changes, the current unbalanced degree can be used as a unified variable to analyze the reduced losses of the distribution network when the EPT is used to compensate the unbalanced current.

IV. COMPREHENSIVE POWER LOSSES MODEL AND SENSITIVITY ANALYSIS

A. COMPREHENSIVE POWER LOSSES MODEL FOR EPT

Considering the EPT power losses P_E and the conventional transformer power losses P_C, and taking into account the reduced losses on the lines caused by the application of EPT, the total reduced losses ΔP can be expressed as,

$$\Delta P = P_C + \Delta P_l + \Delta P_t - P_E = \frac{I^2 R}{\cos^2 \varphi} + (3I^2 R + \frac{6I^2}{R})\varepsilon^2 - I^2 R + P(\rho_1 - \rho_2) \tag{27}$$

P_l is the lines power losses in normal operating conditions ($\cos\varphi_0 = 1$, $\varepsilon = 0$), $P_l = I^2 R$. Therefore, ΔP can be simplified as follows,

$$\Delta P = \frac{P_l}{\cos^2 \varphi} + (3P_l + \frac{6P_l}{R^2})\varepsilon^2 - P_l + P(\rho_1 - \rho_2) \tag{28}$$

Based on ΔP, the condition in which the reduced losses ΔP satisfy $\Delta P \geq 0$ with balanced three-phase current ($\varepsilon = 0$) is,

$$\cos^2 \varphi \leq \frac{I^2 R}{I^2 R + P(\rho_1 - \rho_2)} \tag{29}$$

where ρ_1 and ρ_2 are the power losses rates of the conventional transformers and the EPT, respectively.

Similarly, when the distribution network operates at the unity power factor ($\cos\varphi_0 = 1$, $\cos\varphi$ can be approximately 1), the condition in which the reduced losses satisfy $\Delta P \geq 0$ is,

$$\varepsilon^2 \geq \frac{PR(\rho_1 - \rho_2)}{3I^2 R^2 + 6I^2} \tag{30}$$

Because the EPT power losses rate ρ_1 is much higher than the conventional transformer power losses rate ρ_2, so from (29) and (30), it can be seen that it requires a very low power factor or a high current unbalanced degree if the $\Delta P \geq 0$ is satisfied under a single factor. However, the actual distribution network can't operate in this condition. Therefore, in the case of non-unity power factor and three-phase unbalanced current, the reduced power losses in the actual distribution network need a comprehensive consideration.

Based on the comprehensive analyses, when $\Delta P \geq 0$, the power factor φ_0 and current unbalanced degree ε should satisfy the following conditions,

$$\frac{1}{\cos^2 \varphi} + (3 + \frac{6}{R^2})\varepsilon^2 \geq 1 + \frac{1}{\rho}(\rho_1 - \rho_2) \qquad \cos\varphi = \frac{S\cos\varphi_0 + P_b}{S + \sqrt{Q_b^2 + P_b^2}} \tag{31}$$

where ρ is the lines losses rate in the case of unity power factor and balanced three-phase current.

Using the EPT to replace the conventional transformer can reduce the power losses in the above conditions. And it can be seen from (31) that the longer the distribution lines, the more extensive the applicability of the EPT. So, the EPT can be more applicable in the distribution network which requires long distance transmission lines.

B. SENSITIVITY ANALYSIS

In order to provide a clear picture for the losses reduction caused by the application of the EPT in the distribution network, the respective power losses reduction caused by the power factor correction and unbalanced current compensation are studied in detail. An overall sensitivity analysis for the EPT comprehensive power losses model is carried out to compare the ΔP_l and ΔP_t in different cases.

The condition in which the power factor has a bigger effect on the ΔP is,

$$\Delta P_l \geq \Delta P_t \Rightarrow \frac{1}{\cos^2 \varphi} \geq 3\varepsilon^2 + \frac{6\varepsilon^2}{R^2} + 1 \tag{32}$$

It can be seen from (32) that the distribution lines resistance has a greater impact on the reduced losses caused by the unbalanced current. Therefore, when the distribution network has longer lines, the reduced losses caused by the unbalanced current compensation are bigger than that caused by the power factor correction. And in the long-distance transmission networks, the EPT is more economical for the three-phase unbalanced area.

In the meantime, as the parameters of the distribution network are dynamically changing, the losses parameters sensitivity need to be analyzed by comparing the impact of slight variations of the power factor and the current unbalanced degree on the EPT comprehensive losses model.

Losses parameters sensitivity analysis is performed at $\Delta P \geq 0$, so the constraint is,

$$\frac{P_l}{\cos^2 \varphi} + (3P_l + \frac{6P_l}{R^2})\varepsilon^2 - P_l + P(\rho_1 - \rho_2) \geq 0 \tag{33}$$

The power factor sensitivity can be defined as,

$$\left|\frac{\partial (\Delta P)}{\partial (\cos \varphi_0)}\right| = \frac{2P_l}{\cos^3 \varphi} \times \frac{S}{S + \sqrt{Q_b^2 + P_b^2}} \tag{34}$$

The current unbalanced degree sensitivity is,

$$\left|\frac{\partial (\Delta P)}{\partial (\varepsilon)}\right| = 6\left(P_l + \frac{2P_l}{R^2}\right)\varepsilon \tag{35}$$

The value of each parameter variation impact on the EPT losses model can be determined by comparing the power factor sensitivity and the current unbalanced degree sensitivity. The greater the losses sensitivity, the bigger the effect of parameter variation.

V. COMPREHENSIVE LOSSES SIMULATION OF DISTRIBUTION NETWORK APPLING EPT

By utilizing the constructed EPT model and simulating the actual operation of the distribution network, a 10-kV distribution network is used for case studies. The constructed EPT adopts the AC/DC/AC model. Its rated capacity is 100 kVA, primary AC voltage is 10 kV, secondary AC voltage is 0.4 kV, primary DC voltage is 4.2 kV, secondary DC voltage is 0.6 kV, the modulation degree is 1, the frequency of the IF transformer is 1000 Hz. The IGBT modules adopt Infineon's FF400R33KF2C, its maximum rated value of the collector-emitter voltage is 3300 V, and the continuous DC collector current is 400 A. The specific IGBT parameters can be obtained from the characteristic curves in the product manual as shown in Fig. 1 and Fig. 2. The AC-DC stage consists of 5 series-connected IGBTs switches with 15% redundancy to withstand 4.2 kV (the DC link voltage), and the DC-AC stage consists of 2 series-connected IGBTs switches. The no-load losses of the conventional transformer in the distribution network are 0.4 kW, the rated load losses are 1.69 kW, the load current percentage is 1.8, and the impedance voltage percentage is 4.0.

The losses are evaluated using both the analytical method and MATLAB software measuring method. First, based on the established EPT losses model, EPT per device losses are shown in Table 1.

It can be seen from Table 1 that the total efficiency of the EPT is low, only 91.4%. Therefore, it is not economical to use the EPT to replace the conventional transformers in the distribution network in general occasions. However, with the development of the higher efficiency power devices and the input of more optimized control strategies, the EPT power losses will gradually decrease, and the EPT maximum efficiency is expected to reach 95%-98%. In the future, it will be economical to use the EPT in general occasions.

TABLE 1. EPT per device losses.

Parts		Losses (kW)	Total power losses(kW)	Efficiency
VAC	Rectifier	2.5953	8.5994	91.4%
	Inverter	1.9434		
H-bridge converters	High voltage	1.5362		
	Low voltage	0.5125		
IF transformer	Core losses	0.305		
	Winding losses	1.707		

The EPT power factor correction function is obvious which will not be discussed in this paper. The following simulations mainly study the three-phase unbalanced current compensation function of the EPT and the power losses caused by the unbalanced current.

Before 0.05s, the distribution system is in the three-phase unbalanced condition. After 0.05s, the EPT starts to apply compensation. In this process, the three-phase current simulation in the substation outlet is shown in Fig. 4.

It can be seen that, with lines compensation, the EPT can maintain the three-phase current in a balanced operating condition. In this process, the losses on the lines are listed in Table 2.

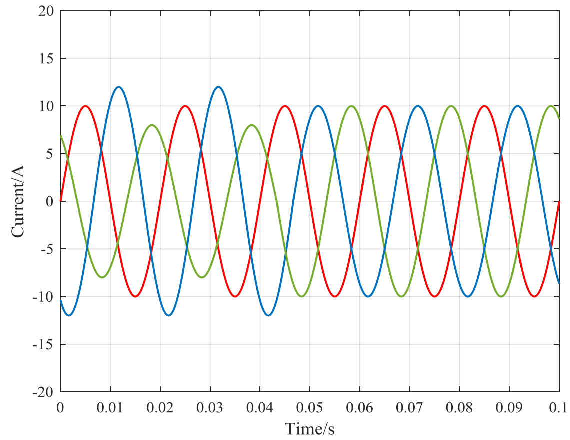


FIGURE 4. Three-phase current in the substation outlet.

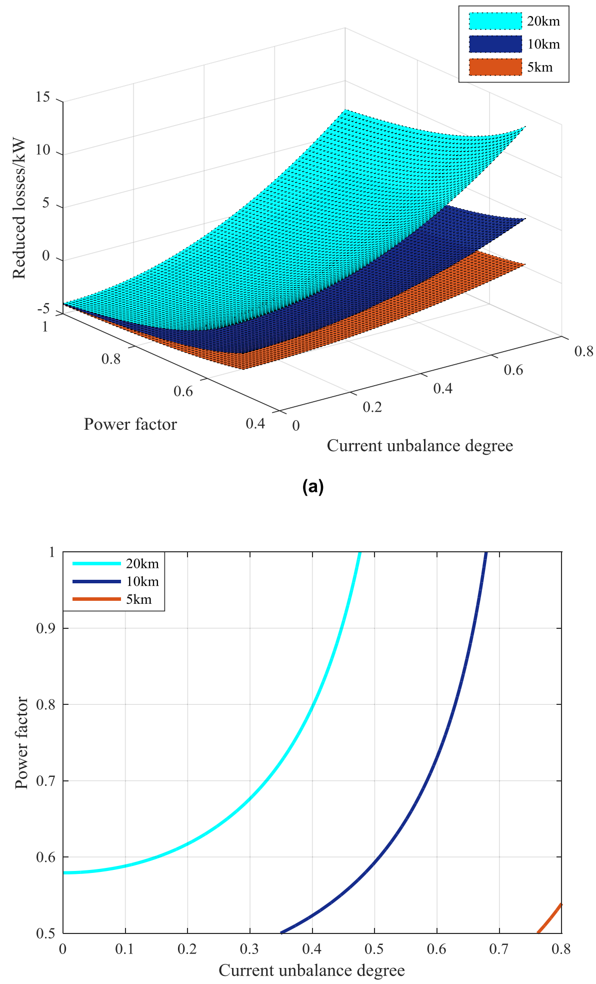
From Table 2, it can be seen that if different unbalanced three-phase current values correspond to the same current unbalanced degree, the reduced power losses after EPT compensation are the same. If there are only single-phase loads in the distribution network, the reduced lines power losses are significant. Therefore, the application of the EPT can effectively reduce the losses caused by the three-phase unbalanced current.

TABLE 2. Contrast before and after compensation.

Current before EPT compensation (A)	Current unbalanced degree	Reduced power losses after EPT compensation
I_a=8, I_b=10, I_c=12 I_a=9, I_b=12.3, I_c=8.7	11.55%	0.2356 kW
I_a=8, I_b=8, I_c=14	20%	0.7068 kW
I_a=8, I_b=6, I_c=16	30.55%	1.6493 kW
I_a=12, I_b=2, I_c=16	40.41%	2.8862 kW
I_a=15, I_b=0, I_c=15	50%	4.4177 kW
I_a=30, I_b=0, I_c=0	100%	17.6706 kW

Taking into account the effect of the three-phase unbalanced current and the non-unity power factor, when the distribution lines are 20 km, 10 km and 5 km, the overall reduced power losses in the distribution network are shown in Fig. 5.

Fig. 5a shows the reduced losses three-dimensional diagram under the comprehensive analysis. Fig. 5b shows the projection of the overall reduced losses on the power factor and the three-phase unbalanced degree at $\Delta P = 0$, that is the applicable critical condition in which the application of EPT instead of conventional transformer can decrease power losses in the distribution network. In this critical condition, power factor and three-phase unbalanced degree are a positive quadratic function. The upper part of the curve is the area where $\Delta P = 0$, in this case, using the EPT to replace the conventional transformer is more economical for the distribution network. It can be also seen from the Fig. 5 that, the longer the distribution lines are, the greater the applicable



(b)

FIGURE 5. Reduced losses in the comprehensive consideration. (a) Reduced losses three-dimensional diagram under the comprehensive analysis. (b) The projection of the overall reduced losses on the power factor and the three-phase unbalanced degree at $\Delta P = 0$.

range will be. Therefore, in terms of distribution network energy-saving, the EPT have a better applicability for the remote rural areas, the industrial and enterprise distribution networks or the electric transit and railroad systems away from the power center.

Fig. 6 shows the comparison of the ΔP_t and ΔP_l. The upper part of the curve is the area where the application of EPT can reduce more losses caused by the unbalanced current, and the lower part of the curve is the area where the application of the EPT can reduce more losses caused by the non-unity power factor. As the reactive power losses exist in the conventional transformer, the EPT can still reduce additional power losses although the load power factor is at 1, which is verified in the simulation results.

Fig. 7 shows the comparison of each parameter sensitivity. The upper part of the curve is the area where the current unbalanced degree sensitivity is larger, and the lower part of the curve is the area where the power factor sensitivity is larger. Therefore, it can be seen from the Fig. 7 that, the variation of power factor has a greater impact on the losses

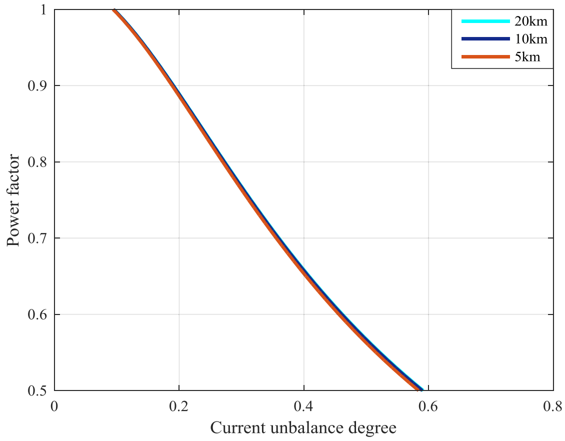


FIGURE 6. Comparison of ΔP_t and ΔP_l.

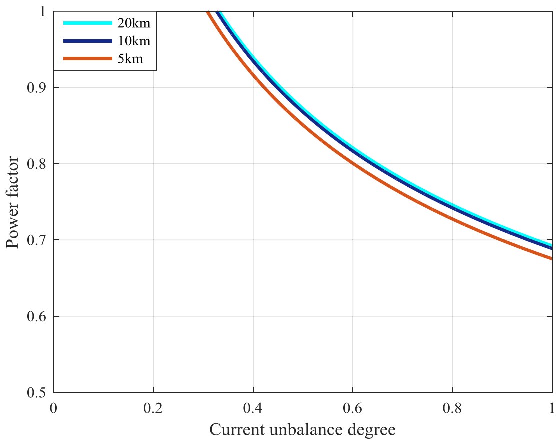


FIGURE 7. Comparison of each parameter sensitivity.

reduction when the power factor is less than 0.68 or current unbalanced degree is less than 0.3 in this illustrative example.

VI. CONCLUSION

The EPT has higher power losses than the conventional transformer. However, it can correct the power factor, compensate the unbalanced current, and reduce the overall losses in the distribution network. Therefore, a comprehensive EPT losses analysis model is proposed in this paper. By building the comprehensive EPT power losses model, taking into account the power losses of the EPT, conventional transformer and the reduced losses of the lines caused by the application of the EPT, using the EPT to replace the conventional transformer in distribution networks can decrease the overall power losses. It can be deployed in remote rural areas, industrial and enterprise distribution networks or electric transit and railroad systems away from the power center.

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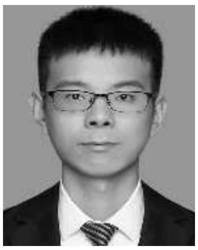

QUANYOU YUE was born in Anyang, Henan Province, China, in 1991. He received the B.Sc. degree in electrical engineering from Hunan University, Changsha, China, in 2015, where he is currently pursuing the M.Eng. degree in power systems with the College of Electrical and Information Engineering. His research interests include electronic power transformer's application and energy efficiency.

CANBING LI (M'06–SM'13) was born in Yiyang, Hunan Province, China, in 1979. He received the B.Sc. and Ph.D. degrees in electrical engineering from Tsinghua University, Beijing, China, in 2001 and 2006, respectively. He is currently a Professor with the College of Electrical and Information Engineering, Hunan University, Changsha, China. His research interests include smart grid, energy efficiency, and energy policy.

YIJIA CAO (M'98–SM'13) was born in Yiyang, Hunan Province, China, in 1969. He received the B.Sc. degree in electrical engineering from Xi'an Jiaotong University, Xi'an, China, in 1988, and the Ph.D. degree from the Huazhong University of Science and Technology, Wuhan, China, in 1994. He is currently a Chair Professor and the Vice President with the College of Electrical and Information Engineering, Hunan University, Changsha, China. His research interests include power system cascading failure, smart grid information technology, smart grid operation, and optimization.

YUQING HE received the B.S., M.S., and Ph.D. degrees in electrical engineering from Hunan University, China, in 2005, 2008, and 2011, respectively. He has been with Hunan University since 2001. He is currently with the Hunan Electric Power Corporation Research Institute. His interests include power system economics and power system reliability and operation.

BINGLIN CAI received the B.Sc. degree in electrical engineering from Zhengzhou University, Zhengzhou, China, in 2016. He is currently pursuing the M.Eng. degree in power systems with the College of Electrical and Information Engineering, Hunan University, Changsha, China. His research interests include smart grid and power market.

QIUWEI WU (M'08–SM'15) received the B.Eng. and M.Eng. degrees in power system and its automation from the Nanjing University of Science and Technology, Nanjing, China, in 2000 and 2003, respectively, and the Ph.D. degree in power system engineering from Nanyang Technological University, Singapore, in 2009.

He was a Senior Research and Development Engineer with VESTAS Technology Research and Development Singapore Pte Ltd from 2008 to 2009. He was a Visiting Scholar with the Department of Industrial Engineering and Operations Research, University of California, Berkeley, CA, USA, from 2012 to 2012, funded by the Danish Agency for Science, Technology and Innovation, Denmark. He was a Visiting Professor named by Y. Xue, an Academician of the Chinese Academy of Engineering, Shandong University, China, from 2015 to 2017. He has been with the Department of Electrical Engineering, Technical University of Denmark, since 2009, where he held a post-doctoral position from 2009 to 2010 and was an Assistant Professor from 2010 to 2013 and has been an Associate Professor since 2013. He is currently a Visiting Scholar with the School of Engineering and Applied Science, Harvard University.

His research area is power system operation and control with high renewables, including wind power modeling and control, active distribution networks, and integrated energy systems. He is an Editor of the IEEE Transactions on Smart Grid and the IEEE Power Engineering Letters. He is also an Associate Editor of the *International Journal of Electrical Power and Energy Systems*, the *Journal of Modern Power Systems and Clean Energy*, and the *IET Renewable Power Generation*.

BIN ZHOU (S'11–M'13–SM'17) was born in Hengyang, Hunan Province, China, in 1984. He received the B.Sc. degree in electrical engineering from Zhengzhou University, Zhengzhou, China, in 2006, the M.S. degree in electrical engineering from the South China University of Technology, Guangzhou, China, in 2009, and the Ph.D. degree from The Hong Kong Polytechnic University, Hong Kong, in 2013. He was a Research Associate and a Post-Doctoral Fellow with the Department of Electrical Engineering, The Hong Kong Polytechnic University. He is currently an Associate Professor with the College of Electrical and Information Engineering, Hunan University, Changsha, China. His main fields of research include smart grid operation and planning, renewable energy generation, and energy efficiency.