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The Transformer Equipment Selection's Update Decision Technical and Economic Analysis Model

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ABSTRACT

Based on the current situation of the domestic transformer equipment selection, the paper analyses the SH15, S11 and S9 transformer from the angles of annual running power consumption, payback period, energy efficiency of the transformer, furthermore, determine the best optimal capacity, load factor and update Year of the SH15-type transformers. Example analysis results show that, from the point of view of the technical and economic the SH15-type transformer has better economic and environmental benefits, and large capacity SH15 transformer better comprehensive benefits.

Keywords: Transformer; Equipment Updates Decision; Technical and Economic Analysis

1. Introduction

With the promotion of building saving type society in China, improving energy efficiency and reducing energy consumption have become an important aspect in decision-making of power grid. As essential equipment in power system, transformer has characteristics of large quantities, great losses and low degree of automation which makes it becomes the focus of power grid to reduce energy consumption. For users, they will achieve the best economic benefits only when the transformer is running at full capacity, but it will increase transformer's energy consumption then lead to a further increase in power network loss. Related literature shows that one third of power network loss come from transformers, reducing transformer's loss has significance in controlling the overall power net loss[1].

The common types of transformer in China are SH15, SH11 and S9, the mainstream of them is S11. Comparing these three kinds of transformer's operating parameters, SH15 transformer has the highest energy-saving efficiency, but it is not widely used because of its cost [2, 3]. Combined with the current situation of China's transformer selection, we select transformer type from the initial investment of the equipments and operation cost of management perspective, without a fully consideration for the energy-saving benefit of transformers. With the implementation of energy-saving and emission-reducing in power grid, energy-saving benefit of transformer will become another decision-making factor in transformer selection, which makes the research on transformer selection and updating decision have important practical significance.

Based on the research status of transformer selection, this paper analyzed transformer SH15, S11 and S9 by using indicators from technological economics and compared their annual power consumption, payback period, energy-saving benefit and decision-making in upgrade, provided recommendations for transformer selection.

2. Analysis Model of Energy-saving and Consumption-reducing Impact on Transformer Selection

1) Calculation model of transformer's annual power consumption

$$pz=p+k_q \bullet q \tag{1}$$

$$p=p_0+k_T \bullet \beta^2 \bullet p_k \tag{2}$$

$$q=q_0+k_T \bullet \beta^2 \bullet q_k \tag{3}$$

In the formula: pz is comprehensive power loss of transformer; p is the active power loss of transformer; q is the reactive power loss of transformer, kw; k_q is reactive economic equivalent; p_0 is no-load loss; p_k is rated load loss; q_0 is reactive no-load loss; q_k is rated load loss; k_T is the coefficient of load fluctuation loss; β is the average load factor.

The average load factor is transformer's load rate; the coefficient of load fluctuation loss means in a certain period, the ratio between load loss caused by transformer's load fluctuation and transformer's average load loss, usually, it ranges from 1 to 1.3.

Reactive no-load loss and rated load loss can be calculated by formula (4) and (5):

$$q_0=\frac{I_0 \bullet S_N}{100} \tag{4}$$

$$q_k=\frac{U_k \bullet S_N}{100} \tag{5}$$

In the formula: I_0 is the percentage of no-load current; U_k is the percentage of impedance voltage; S_N is transformer rated capacity; according to formula (1-5), annual electricity consumption can be calculated as follows:

$$Qtransf=T_0 \bullet \left[\begin{array}{l} p_0+k_T \bullet \beta^2 \bullet p_k+ \\ k_q \bullet \left(\begin{array}{l} \frac{I_0 \bullet S_N}{100}+ \\ k_T \bullet \beta^2 \bullet \frac{U_k \bullet S_N}{100} \end{array}\right) \end{array}\right] \tag{6}$$

Simplified to:

$$\begin{aligned} Qtransf=T_0 \bullet \left(p_0+k_q \bullet \frac{I_0 \bullet S_N}{100}\right) \\ +T_0 \bullet k_T \bullet \beta^2 \bullet \left(p_k+k_q \bullet \frac{U_k \bullet S_N}{100}\right) \end{aligned} \tag{7}$$

In the formula: $Qtransf$ is annual electricity consumption of transformer; T_0 is the hours of unloading condition in a whole year.

2) Analysis model of electricity-saving effect

$$\begin{cases} \Delta Qtransf=\sum_{t=1}^{T} \Delta Qtransf^{\,t} \\ \Delta Qtransf^{\,t}=Qtransf_1^{\,t}\text{-}Qtransf_2^{\,t} \\ \Delta Qtransf^{\,t}\%=\frac{Qtransf_1^{\,t}\text{-}Qtransf_2^{\,t}}{Qtransf_1^{\,t}} \end{cases} \tag{8}$$

In the formula: $\Delta Qtransf$ is cumulative electricity-saving quantity of replacing transformer type1 with type2 in T years; $\Delta Qtransf^{\,t}$ is electricity-saving quantity of replacing transformer type1 with type2 in the tth year; $\Delta Qtransf^{\,t}\%$ is the percentage of replacing transformer type1 with type2 in the tth year; $Qtransf_1^{\,t}$ is power consumption of transformer type1 in the tth year; $Qtransf_2^{\,t}$ is power consumption of transformer type2 in the tth year; η is CO_2 emission coefficient of per unit electric energy, equals to 0.983kg/kWh.

3. Calculation Model of Energy-saving Benefit of Transformer Selection

1) Annual running cost of transformer

$$C=Pelec \bullet Qtransf \tag{9}$$

In the formula, C is transformer's annual cost of electricity consumption; $Pelec$ is electricity price.

2) Energy-saving benefit of transformer selection

$$\begin{cases} \Delta C=\sum_{t=1}^{T} \Delta C^t \\ \Delta C^t=C_1^t\text{-}C_2^t \\ \Delta C^t\%=\frac{C_1^t\text{-}C_2^t}{C_1^t} \\ \Delta CO_2=\Delta Qtransf \cdot \eta \end{cases} \tag{10}$$

In the formula: ΔC is cumulative electricity saving cost of replacing transformer type1 with type 2 in T years; ΔC^t is electricity saving cost of replacing transformer type1 with type 2 in the tth year; $\Delta C^t\%$ is the percentage of electricity saving cost of replacing transformer type1 with type 2 in the tth year; C_1^t is electricity cost of transformer type1 in the tth year; C_2^t is electricity cost of transformer type2 in the tth year.

4. Decision Analysis Model of Transformer Upgrade

1) Payback period of equipment energy-saving selection

$$\sum_{t=1}^{T_p} \Delta C^t=Ptransf_2\text{-}Ptransf_1 \tag{11}$$

In formula (14): T_p is the payback period of transformer type 2 replaces transformer type 1; $Ptransf_1$ is the cost of transformer type 1; $Ptransf_2$ is the cost of transformer type2.

Assume that transformer's work condition remain unchanged, the power cost is equal in each year. Thus, according to formula (1), the payback period is:

$$T_p=\frac{Ptransf_2\text{-}Ptransf_1}{\Delta C^t} \tag{12}$$

Set the year of transformer's service life is T_{plan}. If $T_p>T_{plan}$, it is not economical when transformer type 2 replaces transformer type 1; if $T_p<T_{plan}$, transformer type 2 replaces transformer type 1 can save energy and reduce cost; if $T_p=T_{plan}$, the cost neither increase nor decrease, but the replacement can save energy, for the overall society's benefit, it should be chosen as a solution.

2) Benefits of the selection

$$\Delta R=\Delta C\text{-}\left(Ptransf_2\text{-}Ptransf_1\right) \tag{13}$$

In formula (16), ΔR is the benefit of the replacement (transformer type 2 replaces transformer type 1) in T years. When $\Delta R<0$, choose type 1; when $\Delta R \geq 0$, choose type2.

3) Decision-making model of equipment upgrade based on service life

$$\sum_{t=T_J+1}^{T_{plan,1}} \Delta C^t=\frac{T_{plan,1}\text{-}T_J}{T_{plan,2}} Ptransf_2 \tag{14}$$

In formula (17), T_J is the year of transformer type 1's service life under the condition of upgrading transformer type 1 to type 2 is economical; $T_{plan,1}$ is service life of transformer type 1 as planned; $T_{plan,2}$ is service life of transformer type2 as planned.

When $T_J \leq 0$, transformer type 1 can be upgraded to type 2 at any time; when $T_{plan,1}$-$T_{plan,2} \leq T_J \leq T_{plan,1}$, the actual service time exceed T_J, transformer type1 can be upgraded to type2; when formula (14) has no solution, then it is not economical to upgrade transformer type 1 to type 2 when transformer type 1 is still in its service life.

When $T_J < T_{plan,1}$-$T_{plan,2}$, formula (14) is invalid, at this time, the decision model is:

$$\sum_{t=T_J^{'}+1}^{T_J^{'}+T_{plan,2}} \Delta C^t = Ptransf_2 \tag{15}$$

If $T_J^{'} < T_{plan,1}$-$T_{plan,2}$, the actual service time exceed T_J, in this case, usually, transformer type1 can be upgraded to type2 at any time; if formula (18) has no solution, then it is not economical to upgrade transformer type 1 to type 2 when transformer type 1 is still in its service life.

Assume that transformer's work condition remain unchanged, the power cost is equal in each year. Then the decision-making model can be transformed into the judgment condition:

$$\frac{Ptransf_2}{T_{plan,2}} \leq \Delta C^t \tag{16}$$

If the above condition is workable, then transformer type 1 can be upgraded to type 2 at any time; if the above condition is not satisfied, then it is not economical to upgrade transformer type 1 to type 2 when transformer type 1 is still in its service life.

If $T_{plan,2} = T_{plan,1}$-T_J, the transformer's service life is not extended after upgrade, then decision-making can be made by solving formula (14).

$$T_J = T_{plan,1} - \frac{Ptransf_2}{\Delta C^t} \tag{17}$$

when $0 \leq T_J \leq T_{plan,1}$, the actual service life is less than T_J, transformer type 1 can be upgraded to type 2, otherwise the upgrade cannot be economical.

5. Case Study

5.1. Basic Data

Currently, energy-saving transformers mainly include SH15 amorphous distribution transformer, S11 series distribution transformer, dry type distribution transformer, amorphous alloy transformer, single-phase winding core distribution transformer, OLTC distribution transformer, box type transformer, etc. To analyze the energy-saving effect and selection method of transformers, this paper choose SH15 amorphous alloy transformer with three phase oil-immersed and S9, S11 type conventional core material three-phase oil-immersed transformer, related technical parameters are shown in **Table 1**, the transformers' operating parameters are shown in **Table 2**.

5.2. Results

1) Initial case result

In accordance with the provisions of the standard technical parameters of 10kV distribution transformers of various models, the annual operation cost of different types with different capacity may be determined based on formula (7) and equation (12), as is shown in **Figure 1**. According to **Figure 1** we can see, SH15 type transformer has the lowest annual operating cost, followed is S11 type transformer and then S9 type transformer, and when the transformer's capacity exceeds 400kVA, SH15-type transformers' annual operating cost decrease much more. Combined with the no-load loss in **Table 1**, we can see that SH15-type transformer's no-load loss is 1/3 of the S11-type's and 1/4 of the S9-type's, thus, we can see that S15-type is more economical.

Table 1. Parameters of S11-type and S9-type power transformer.

Transformer type	Rated capacity / kVA	No-load loss / kW	Load loss / kW	No-load current / %	Impedance voltage / %	Equipment cost / (yuan/ kVA)
S9	1000	1.7	10.3	0.8	4.5	84.08
S11	1000	1.15	10.3	0.2	4.5	101.1
SH15	1000	0.45	10.3	0.3	4.5	117.1

Table 2. Transformer operating parameters.

Average load factor	Load fluctuation loss factor	Reactive economic equivalent (kW / kVar)	Transformer age limit (year)	No-load time in one year (hours)	Electricity price (yuan / kWh)
75%	1.12	0.1	20	8600	0.55

We use the designed age limit as using years when calculate, we can see from **Figure 1**, the differences for price between SH15 and S11 is about 33.2 yuan/kVA, and 17.02 yuan/kVA between S11 and S9, then according to the submodels of transformer selection and energy-saving model, we can get the following parameters which is shown in **Table 3**.

We can make the following conclusions by **Table 3**:

a) When SH15-type transformer replaces or upgrades S11 type, the additional investment takes 5.64 years to recover, the equipment's upgrade decision-making model can replace or upgrade at any time, so S15 has a better economy which is because that comparing with S11-type, SH15-type transformer's equipment cost rises relatively low, and every year they can bring electricity cost savings;

b) Compared with S9, SH15 can achieve a cumulative energy-saving power 301000kW and CO_2 emission reduction 295883kg, due to when undertaking a displacement of SH15 to S9, the annual electricity savings is higher than SH15 replaces S11, which makes it take only 3.99 years to recover investment. SH15-type transformer replaced S9 simply additional, the best year for equipment upgrade decisions is within 6 years of S9 type transformer, which is the most economical;

c) In contrast with S9, S11 can achieve 194437.4kg savings in CO_2 emission, additional investment takes 3.13 years to recover, which reduces 0.66 years compared with S15's displacement of S9, but has a significant decline in electricity consumption and CO_2 emission savings.

Based on above analysis, when during period of transformer selection, upgrades and replacement, we should give priority to replace or upgrade the S11 and S9 type transformer by SH15 type, which can fully realize the economic and environmental benefits of SH15-type transformer.

2) Sensitivity analysis

The initial case results show a better practical value of SH15 than S11 and S9 type transformer. The initial case is calculated under a 1000 kVA transformer capacity and average load factor is 75%, in order to further analyze the SH15-type transformers' economic and environmental benefits in different models and load factor, this section selects transformer capacity and load factor as sensitive indicators and make a sensitivity analysis of energy efficiency amount of electricity savings and additional investment payback period for the transformers, specific results are shown in **Figure 2** and **Figure 3**.

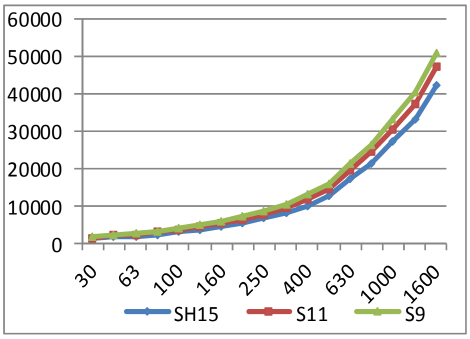

Figure 1. Annual operating costs of the different types of transformers (yuan).

Table 3. Parameters of selection model.

Type in contrast	energy saving/kW	electricity saving/yuan	emission reduction /kg	Payback period/year	income/yuan	upgrade decision	upgrade age
SH15 and S11	103200	56760	101445.6	5.64	40760	1	anytime
SH15 and S9	301000	165550	295883	3.99	132530	1	5.85
S11 and S9	197800	108790	194437.4	3.13	91770	1	1.41

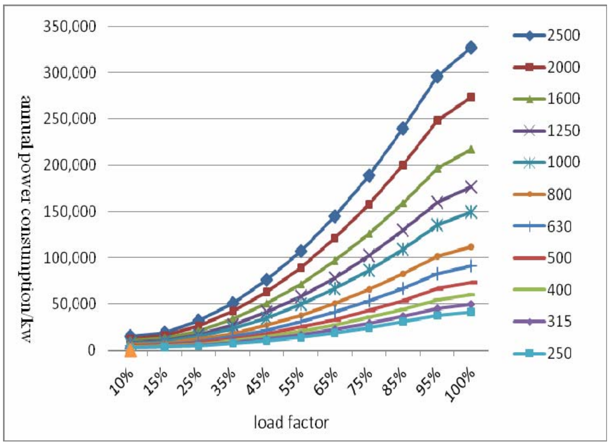

Figure 2. The synthetic losses of SH15 transformer under different load factor and different capacity.

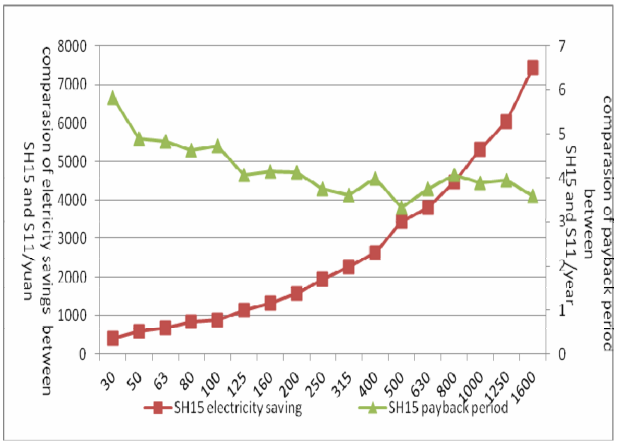

Figure 3. Electricity savings and payback period of the SH15 and the S11 transformer.

We can get that in **Figure 3**, the transformer's capacity and load factor has a direct impact on its power consumption. First considering the transformer capacity, with a gradual increase in the capacity, its annual operating power consumption also showed a growing trend, in which, when the load factor exceeds 25% , its growth rate is the fastest and energy efficiency the highest; then considering load factor, when the transformer's capacity stays unchanged, with the increase of load factor, annual power consumption gradually increases, in the range of 25% to 85%, it has a higher efficiency and energy efficiency. Thus, during SH15-type transformers' selection, large capacity transformer is more appropriate.

In view of economics, during transformer selection, we cannot consider its economic and environmental efficiency indicators but need to analyze the additional investment payback period and amount of electricity savings when selecting new transformers, it can directly reflect the selected transformer type's economic feasibility.

According to **Figure 2** we can know, when transformers in low capacity, compared to the S11 type transformer, SH15 has a longer payback period for additional investment; when in larger capacity, SH15-type transformers' additional investment payback period is relatively short and it has a higher cost-effective, when in 500kVA, the payback period reached its lowest point of 3.32 years, but by the impact of higher requirements for SH15-type amorphous alloy transformer core production process, when the transformer capacity is too large, the years of payback period will increase; overall, when the transformer capacity is in the [250,800] interval, SH15-type transformer additional years of investment recovery is below the average.

In summary, according to the conclusions of sensitivity analysis, we can know that, when making selection of the SH15-type transformers, large-capacity transformer has higher energy efficiency, and has a relatively short additional investment capital recovery period, large capacity SH15 type transformer can better achieve its economic and environmental value.

6. Conclusions

By comparing SH15-type transformer with S11 and S9 type, we find that SH15-type transformer has a better economic and environmental benefit. By using SH15-type transformers to replace or upgrade the S11 and S9 type transformer, we can respectively achieve savings 103200 and 301000 kWh. SH15-type transformers can respectively a achieve CO_2 reduction of 101445.6 and 295883 kg.

1) By sensitivity analysis of the transformers' capacity and average load, we can see that, in larger capacity condition, SH15-type transformer has greater energy efficiency, more electricity savings and its payback period is relatively low.

2) After the sensitivity analysis finds the SH15-type transformer has a better economic and environmental benefit, the paper further calculates the optimal load factor of SH15 type transformer in different capacity and finds that when the load factor lies between 20% and 25%, the transformer has its maximum power and highest energy efficiency.

3) The economic evaluation index in this paper is static, we don't consider the time value of money, but in actual project, it is often taken into consideration, which requires further research on dynamic economic evaluation for transformer selection.

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