Transformer Inter-Turn Faults Detection by Dynamic State Estimation Method

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***Abstract*- Transformers are protected by relays to ensure the overall reliability of the generation, transmission, and distribution electric systems. Among all kinds of transformer faults, the inter-turn faults are considered to be the most difficult faults to be detected. Inter-turn faults are extremely harmful to power transformers. When only few turns are shorted at the windings, the currents in the shorted loop can be very high while the transformer terminal currents change little. It is very difficult for the commercial relays or legacy protection methods to detect the existence of inter-turn faults. In this paper, the dynamic state estimation (DSE) based protection scheme is used to detect inter-turn faults. This method monitors the transformer terminal measurements, and it feeds the measurement data and transformer model to a dynamic state estimator. A chi-square test is performed to evaluate the probability (confidence-level) that the transformer model matches measurement data. Any mismatch between the model and measurement indicates something wrong inside the transformer, and protection action should be taken. Numerical simulations are conducted on a 115/10kV three-phase transformer with a 1% inter-turn fault. Three protection methods are compared, namely the percentage-differential scheme, negative-sequence differential scheme and the proposed DSE-based scheme. Analysis shows that the DSE-based protection is more sensitive and reliable than the other two methods, and in general provides faster protection speed.**

***Index Terms*- Transformer inter-turn fault, dynamic state estimation, differential protection, AQCF model**

I. INTRODUCTION

Transformers are expensive and critical power system components that relate to the overall reliability of the generation, transmission, and distribution electric systems. To guarantee the security of transformers and the stability of the electric grids, transformers should be carefully protected against all kinds of possible failures. According to statistics, more than 70% of transformer failures are caused by shorted circuits [1]-[2]. If the winding insulator is worn out, one or more sequential turns will be shorted, and this situation is known as the inter-turn or turn-to-turn fault. Inter-turn faults are extremely harmful to power transformers. If not being detected in its earliest stage, the inter-turn fault may evolve to irreparable transformer failures. When inter-turn faults happen, the terminal currents do not change much. However, fault currents flowing though the shorted circuit can be tremendously high. The high fault currents generate serious heat that causes localized thermal overloading, which ultimately evolves to catastrophic failures [3]-[4]. Therefore, sensitive and fast protection methods are required to detect inter-turn faults in their earliest stage before further damages occur to the transformers.

Percentage-differential protection scheme is one of the most popular legacy protection schemes for transformers [5]. This scheme is based on a comparison of currents at primary and secondary sides of transformers. If an internal fault happens, it is expected to detect a substantial differential current and then trip the transformer. However, in most cases inter-turn faults do not generate enough differential currents to be detected by the percentage-differential scheme. Negative-sequence differential protection scheme is typically used in the industry to detect the inter-turn faults [6]-[7], because inter-turn faults cause asymmetries of transformer terminal currents. Negative-sequence currents at the primary and secondary sides are good indicators of inter-turn faults. However, the negative-sequence differential scheme is not sensitive enough to detect some intern-turn faults involving only very few turns [8]. In recent years, other methods using fuzzy-logic, neural network (ANN) or wavelets have also been studied for detecting inter-turn faults [9]-[11]. However, these methods require large training sets and it is possible that they cannot cover all the possible situations that could happen in the real world. Moreover, some of the methods also require expensive specialized apparatus which may not be feasible for transformers. A dynamic state estimation (DSE) based scheme has been proposed to protect the transformer [12]-[13]. The dynamic states are continuously estimated from measurements and the protective decision is based on the transformer states only. This method has been implemented successfully to protect transformers against turn-to-ground faults.

This paper applies the DSE-based protection scheme to detect the transformer inter-turn faults. The fundamental idea of the proposed DSE-based method it to check the

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consistency between the transformer dynamic model and measurements at the terminals and/or inside the transformer. Any mismatch between the model and measurement indicates something wrong inside the transformer, and protection actions should be taken.

A three-phase transformer is used for the comparison of three protection methods: the percentage-differential scheme, the negative-sequence differential scheme, and the DSE-based scheme. The three-phase transformer is expressed in an object in the algebraic quadratic companion form (AQCF) [14]-[15]. The model of this three-phase transformer consists of three single-phase transformer, and details of the single-phase transformer are presented in this paper. The measurements are also expressed in an object with similar syntax as the AQCF. The dynamic state estimation algorithm operates directly with the model and measurements expressed in the above objects, therefore the proposed DSE-based method is object-oriented.

This paper is organized as follows. In Section II, the AQCF model of transformers with inter-turn faults, as well as three protection methods are discussed. In Section III, the hardware-in-the-loop simulation is present. In Section IV, numerical simulations of a three-phase transformer with inter-turn faults are conducted and the performance of three protection methods are compared. Section V presents conclusions.

II. Transformer With Inter-turn Faults

This section will first give a description of the transformer model with the inter-turn faults. Then three protection methods for the inter-turn faults are discussed.

A. *Transformer AQCF model with inter-turn faults*

The model of transformer with user-defined inter-turn fault is introduced by a single-phase transformer with two-windings, as is shown in Figure 1. Note the percentage α and β are the user-defined percentile positions where the inter-turn fault happens.

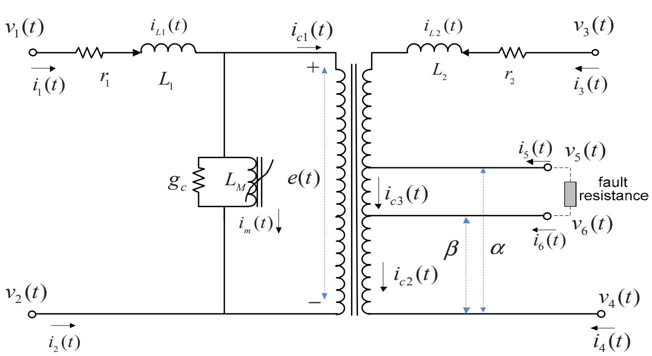

Figure 1. Model of transformer with inter-turn faults

The model of a single-phase transformer with user-defined inter-turn fault is given in the algebraic quadratic companion form (AQCF) as follows:

$$\begin{Bmatrix} i(t) \\ 0 \\ i(t_m) \\ 0 \end{Bmatrix} = Y_{eqx}\mathbf{x}(t,t_m) + \begin{Bmatrix} \vdots \\ \mathbf{x}(t,t_m)^T \left\langle F_{eqx}^i \right\rangle \mathbf{x}(t,t_m) \\ \vdots \end{Bmatrix} - B_{eq} \quad (1)$$

where:

$[i(t)\ \ i(t_m)]$ are the currents at transformer terminals at two adjacent time step t and time t_m;

$[x(t)\ \ x(t_m)]$ are the external and internal state variables;

Y_{eqx} and F_{eqx} are the state matrix for transformer linear part and quadratic part;

B_{eqx} is the past history vector of the transformer model.

B. *Percentage-differential protection*

Percentage-differential protection scheme is one of the most popular legacy transformer protection schemes, as shown in Figure 2.

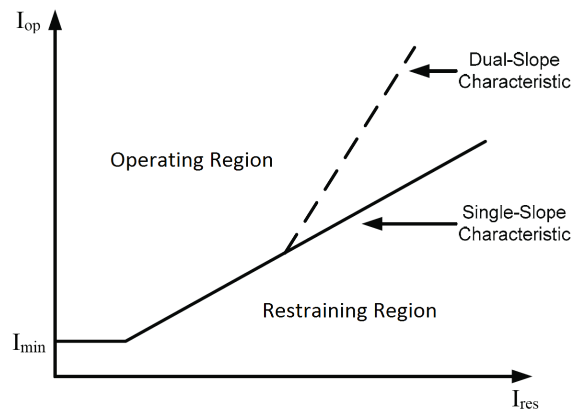

Figure 2. Percentage-differential protection method

It monitors the currents coming to the transformer two terminals $\vec{I}_{s1}$ and $\vec{I}_{s2}$. Then this method calculates the operating current $I_{op} = \left|\vec{I}_{s1} + \vec{I}_{s2}\right|$ and restraining current $I_{res} = \frac{1}{2}\left|\vec{I}_{s1} - \vec{I}_{s2}\right|$. Ideally, the operating current I_{op} remains zero unless an internal fault occurs. However, the existence of variable-tap transformers and instrumentation errors make this simple criterion inappropriate for practical applications. To overcome this problem, a minimum pickup current $I_{\min}$ and differential ratio $K = I_{op} / I_{res}$ are introduced. It will trip the transformer only if (1) $I_{op} > I_{\min}$; and (2) the ratio $K = I_{op} / I_{res}$ exceeds a certain threshold. The threshold is selected to avoid misoperation caused by changes of transformers taps or instrumentation errors, and it is typically set to be 20% ~ 40%. Note that sometimes the dual slope is introduced to provide better reliability, the higher slope when the large external fault happens. The large external fault may cause the asymmetrical saturation of the CTs and a higher slope provides a better toleration.

C. Negative-sequence differential protection

Negative-sequence differential protection is the most effective legacy function that has been implemented in commercial relays for detecting transformer inter-turn faults. It is based on the fact that inter-turn faults create disturbances of the symmetry of transformer terminal currents. Therefore, negative-sequence currents at the primary and secondary sides are good indicators of inter-turn faults. Similar to the percentage-differential protection, this method uses the negative-sequence operating current $I_{op(Q)}$ and negative-sequence restraining current $I_{res(Q)}$ of transformer to make trip decisions. It will trip the transformer only if (1) $I_{op(Q)} > I_{\min(Q)}$; and (2) the ratio $K_{(Q)} = I_{op(Q)} / I_{res(Q)}$ exceeds a preset threshold.

D. DSE-based protection

The DSE-based protection scheme is an extension of differential protection. It measures transformer voltages and currents. The measurement data are then fit to the transformer mathematical model. This is achieved in a mathematical rigorous way by the use of dynamic state estimation. DSE calculates the degree of consistency between measurements and the transformer dynamic model. If there is a mismatch, something is wrong inside the transformer and protective action should be taken.

In contrast to present approaches for numerical relays that the trip decision is based on settings and coordinated logics, the proposed method accurately makes the protection decision only based on the operating condition of the transformer. In this case, some unnecessary relay failures due to improper coordination, or improper settings, or even human errors can be avoided.

Specifically, any transformer measurement can be written in AQCF form at equation (28) as follows:

$$\begin{aligned} z_k(t) = h_k(x) + \eta_k &= \sum_i a^k_{i,t,x} \cdot x_i(t) + \sum_i a^k_{i,tm,x} \cdot x_i(t_m) \\ &+ \sum_{i,j} b^k_{i,j,t,x} \cdot x_i(t) \cdot x_j(t) + \sum_{i,j} b^k_{i,j,tm,x} \cdot x_i(t_m) \cdot x_j(t_m) + c_k(t) + \eta_k \end{aligned} \quad (2)$$

where z is the measurement, a , b and c are the coefficients of linear, nonlinear and constant term, and η is the transformer measurement error.

The weighted least square method is applied here to solve the DSE problem. Mathematically:

$$\mathit{Minimize} \quad J = \sum_{i=1}^{n} \left(\frac{h_i(x) - z_i}{\sigma_i} \right)^2 = \sum_{i=1}^{n} s_i^2 = \eta^T W \eta \quad (3)$$

where $\mathbf{W} = diag\{..., 1/\sigma_i^2, ...\}$, σ_i is the meter error standard deviation including relaxed measurements corresponding to internal constraints. The solution of this objective function is:

$$\mathbf{x}^{v+1} = \mathbf{x}^v - (H^T W H)^{-1} H^T W (h(\mathbf{x}^v) - \mathbf{z}) \quad (4)$$

After obtaining the estimated states from the dynamic state estimation, a chi-square test is then utilized to provide the probability that the expected error of the estimated state values will be within a specific range. This means the chi-provides the probability how much the transformer model and measurement fit together. The probability (confidence level) *Pr* is computed as:

$$Pr[\chi^2 \geq \xi] = 1 - Pr[\chi^2 \leq \xi] = 1 - Pr(\xi, v) \quad (5)$$

where $\boldsymbol{v}$ is the degree of freedom and ξ is the chi-square value:

$$\xi = \sum_i \left(\frac{h_i(x) - z_i}{\sigma_i} \right)^2 \quad (6)$$

A high confidence level implies that the measurements fit the mathematical model and therefore the transformer is in good health, while a low confidence level implies an internal fault. The proposed DSE-based scheme accurately makes the protection decision only based on the operating condition of the transformer.

III. Hardware in the loop laboratory setup

The feasibility of the DSE-based for transformer inter-turn faults is tested through a hardware-in-the-loop (HIL) simulation. The laboratory setup for this simulation is shown in Figure 3.

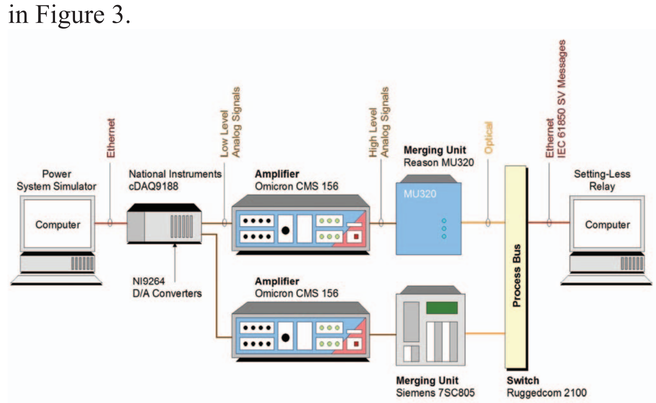

Figure 3. Hardware in the loop laboratory setup

The simulator generates digital data of transformer inter-turn faults events to a D/A converter and they are converted into analogy signals. Then the analogy signals are fed to a bank of amplifiers, by which the signals are amplified to standard range of typical outputs from CT/VTs so that they are used to mimic the actual field signals. These signals coming out of the amplifiers are then transferred to the merging units. The merging unit sampling rate is 4800 samples/sec, and it connects primary events generation system and the DSE-based protection system [16]. It converts the analog signals from analog CT/VT signals to digital signals, which are then transmitted to the process bus via standard protocol (IEC-61850) [17]. The process bus offers the obvious possibility of bringing many measurements (as a matter of fact all the measurements) to the process bus. The GPS is used to synchronize the measurement data at the process bus. At the end of the process bus, a computer is connected to receive the transformer events data. These events data are finally sent to the run the DSE-based protection algorithm.

IV. Numerical Results

In this section, numerical cases are studied for the power transformer inter-turn faults. A 50 MVA, 115/10 kV three-phase delta-wye connected, saturable-core transformer is designated as T1 in Figure 4. The transformer is 50% loaded. An inter-turn fault happens to the phase A of transformer secondary side windings at time t= 30.2 s, shorting 1% of the turns with the percentile position α=0.51 and β=0.5.

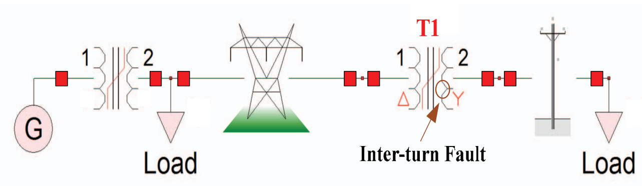

Figure 4. Test system for numerical experiments

The targeted transformer is protected with three methods: (a) percentage-differential protection; (b) negative-sequence differential protection; (c) DSE-based protection. These protection functions have the following settings: (a) percentage-differential protection: minimum pickup current I_{min} is 10A (referred to primary side) and the threshold K_{set} is 20%; (b) negative-sequence differential protection: minimum pickup current $I_{min(Q)}$ is 0.75A (referred to primary side) and the threshold $K_{set(Q)}$ is 20%; (c) DSE-based protection only involves settings of operating limits, such as hot-spot temperature (105 Celsius).

Transformer terminal measurements and the fault current in the shorted-loop are shown in Figure 5 for the time period [30.10-30.27] seconds.

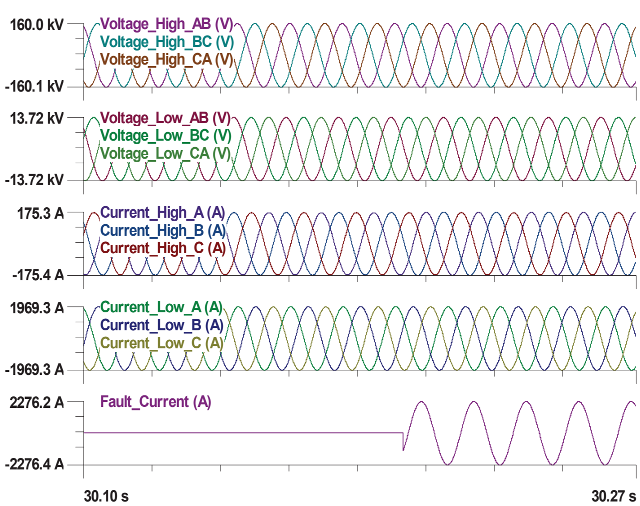

Figure 5. Transformer terminal measurements

The first two sets of traces are the terminal voltages of transformer, the second two sets of traces are the terminal currents of transformer, and the last set of trace is the fault current in the shorted loop. As is shown in Figure 5, the fault current is very high, while there is no obvious change in the terminal currents when the inter-turn fault happens. The results of three protection methods are presented next.

A. Percentage-differential protection

The results of percentage-differential protection scheme are shown in Figure 6. When the 1% inter-turn fault happens, the operating-current I_{op} is about 0.523A (refer to primary side), which is smaller than the 10A setting. The restraining current I_{res} is 122.8A and the differential percent ratio K is 0.426%, and it is also less than the 20% setting. Because both settings are not exceeded, the percentage-differential scheme would not send a trip signal, so it cannot pick up the 1% inter-turn fault in this situation.

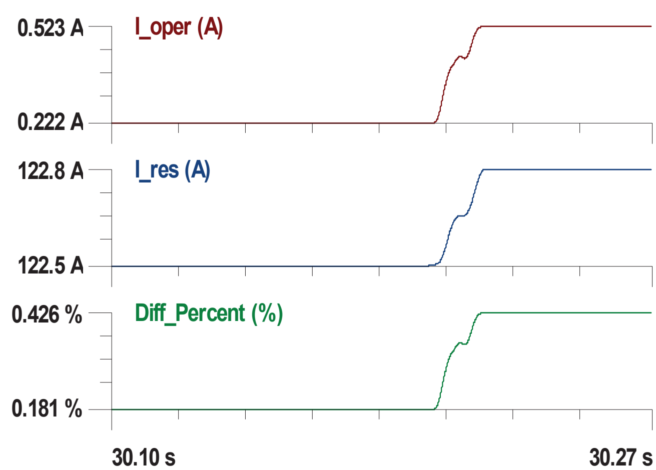

Figure 6. Results of percentage-differential method

B. Negative-sequence differential protection

The results of negative-sequence differential protection scheme are shown in Figure 7. When the 1% inter-turn fault happens, the negative-sequence operating-current $I_{op(Q)}$ is about 0.243A (refer to the primary side), which is smaller than the 0.75A setting. The negative-sequence restraining current $I_{res(Q)}$ is about 1.8A and the negative-sequence differential percent $K_{(Q)}$ is around 14.68%, and it is also less than the 20% setting. Because both settings are not exceeded, the negative-sequence differential function would not send a trip signal, so it cannot pick up the 1% inter-turn fault in this situation as well.

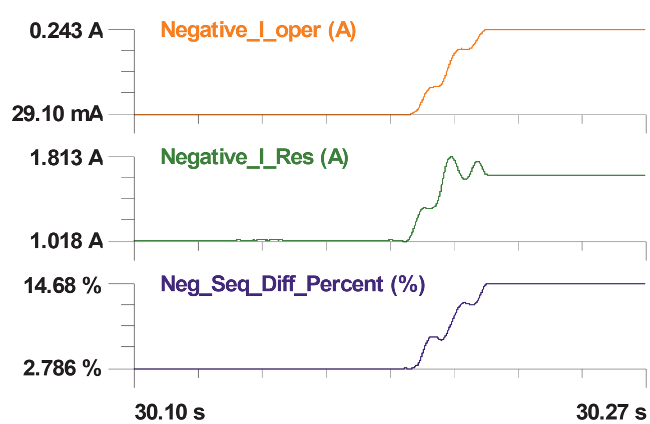

Figure 7. Results of negative-sequence differential method

C. *Dynamic state estimation based protection*

The results of the DSE-based protection method are shown in Figure 8. When the 1% inter-turn fault happens, there are not obvious changes in the terminal currents. However, the residuals of terminal currents increase from zero to considerable values. The chi-square also goes from a very small value to a high one, while the confidence level drops from 100% to zero immediately. This zero value indicates abnormalities inside the transformer and protection action would be taken as soon as possible. It is noticed that confidence level is oscillating during the fault period because the 1% inter-turn fault is too small. An integral function is applied to accumulate the confidence level values and a trip decision is taken to protect the transformer, as shown in Figure 8. It takes about only 0.3ms to detect the existence of fault and another 5ms (which is user-defined) to make the trip decision.

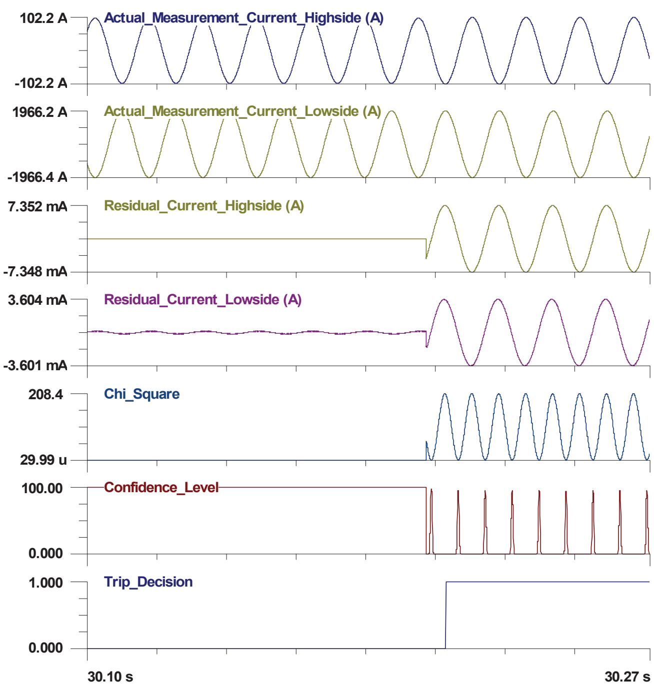

Figure 8. Results of DSE-based method

D. *Comparison of three methods*

Several more events have been tested in respect to 1%~4% inter-turn faults, and the results of three protection methods are shown in Table I. As presented in the table, the percentage-differential scheme fails in all cases for the 1%~4% inter-turn faults. The negative-sequence differential scheme can detect the 2%~4% inter-turn faults, but it fails when the fault is as small as 1%. In contrast, the DSE-based scheme successfully protects transformer against all kinds of inter-turn faults with high reliability (probability of internal fault by DSE is 100%). Note that the 1% inter-turn fault is very harmful to the transformer. The extreme hot at the fault point generated by the shorted current would cause permanent fault to the transformer and it can easily evolve to cascade fault. Therefore, detecting the 1% inter-turn fault at its first stages is very important.

Regarding the protection speed, the DSE-based protection method only takes 0.3ms to detect the existence of fault while the average time required for the negative-sequence differential scheme is about 10ms. That is because the DSE-based scheme theoretically only requires three sample measurements to decide if an internal fault exists, while for the negative-sequence differential scheme it takes much more accumulated samples and additional time to calculate the negative-sequence values. This means the DSE-based scheme is much faster than the negative-sequence differential function.

Table I. Comparison of three protection methods

Fault Percentage	**1%**	**2%**	**3%**	**4%**
I_{op} (in Amps)	0.52	1.51	5.17	9.60
Max K (in %)	0.43	2.11	4.89	7.55
Method 1 Trip? (Y/N)	***N***	***N***	***N***	***N***
$I_{op(Q)}$ (in Amps)	0.24	1.14	2.09	3.30
Max $K_{(Q)}$ (in %)	14.68	25.54	39.31	56.06
Method 2 Trip? (Y/N)	***N***	***Y***	***Y***	***Y***
Probability of internal fault by DSE (in %)	100	100	100	100
Method 3 Trip? (Y/N)	***Y***	***Y***	***Y***	***Y***

V. CONCLUSIONS

This paper describes the dynamic state estimation-based method to protect power transformers against inter-turn faults. The AQCF model of the transformer with user-defined inter-turn faults and hardware-in-the-loop laboratory setup have been introduced. The percentage-differential scheme and the negative-sequence differential scheme have been compared with the DSE-based scheme for different levels of inter-turn faults. Simulation results show the percentage-differential scheme cannot detect inter-turn faults that involve only a few turns; the negative-sequence differential scheme is capable to detect inter-turn faults that involve 2% or more turns; the DSE-based scheme can detect inter-turn faults as small as 1% with high certainty. Results indicate the DSE-based protection scheme is reliable, more sensitive and faster than the other two legacy protection methods.

The DSE-based scheme will be tested on actual power transformers in the near future.

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