Detection of internal faults in transformers using non linear observers

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Abstract– **The develops in transformer construction made the basic principle of the classical differential protection not practicable, when some kind of faults are present in the transformer. Internal faults could not be detected by using differential protection. In this work an approach based on analytical redundancy is applied to the problem of detection of internal faults in the transformer. Using a non linear model of the transformer it is shown how faults could be effectively detected.**

Index Terms-- **Fault detection, Transformer , internal faults, Non-linear Observer.**

I. INTRODUCTION

A common problem in power transformers is the so called internal faults. These include turn to earth and turn to turn faults. If an internal fault is not detected in a very short instant of time, they could produce strong danger in a power system. Different techniques has been used in order to detect these faults, however, the classical tool is the so called differential protection [5]. The develops in transformer construction made the basic principle of differential protection questionable. The effect of the faults on the wave form are not more different to the effect of the nonlinearities on the inrush current. The improvement in the transformer construction produce a difficult to detect some kind of faults. New methods for the early detection of internal faults are required.

Note that frequently methods based on signal processing has been applied to power systems, however, all these methods are based on the same principle and consequently have also the same difficulties.

In this work, an approach based on analytical redundancy [2] is considered. Note that analytical redundancy is conceptually different to the signal processing based methods. Based on a nonlinear model of the transformer, an observer based approach for the detection of internal faults is developed.

The transformer has been modeled considering non linearities as hysteresis and saturation, as proposed in [3]. With the proposed approach it is reduced the possibility of false alarms and improve the early detection of internal faults. The design is tested in different sceneries: First, turn to earth faults are simulated. A detection algorithm based on nonlinear observer is designed and tested. Second, turn to turn faults are simulated and the designed observer-based detector is tested.

The paper is organized as follows: in section 2 the detection of faults using observer-based methods is considered; the model of the transformer is shown in section 3; in section 4 the detection of internal faults is presented; in section 5 some conclusions are given.

II. OBSERVER-BASED FAULT DETECTION APPROACH

The basic idea using observers for the detection of faults is the follow: First redundancy is obtained from the mathematical model of the system. The analytical redundancy is used to obtain an estimated of the nominal value of the system output. The fault detection could be carried out by a comparison of the actual output measurement and its estimated. See Fig 1

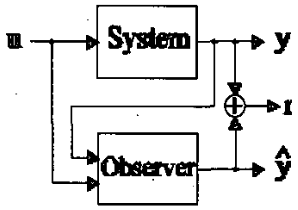

Fig. 1. Basic idea of observer-based methods for fault detection.

The detection of faults could be divided into two steps:

- **Residual generation.** In this step signals depending only on the faults are generated, the so called residuals. If the system is free of faults, the residuals should be zero. If a fault is affecting the system the residuals should be different from zero.
- **Residual evaluation.** The residuals are evaluated in order to determinate if a fault is affecting the system.

III. OBSERVER-BASED APPROACH

Consider a class of non linear systems given by:

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$$\begin{aligned} \dot{x} &= Ax + Bu + \Phi(x) + Ef \\ y &= Cx \end{aligned} \tag{1}$$

where f is a fault considered, $x \in \Re^n$ is the state vector, $y \in \Re^m$ is the output vector and $u \in \Re^p$ is the input vector.

In order to detect a fault f in the model (1), different approaches could be considered. In this work the observer proposed in [8]. Note that other approaches used for fault detection of this kind of systems have been also proposed in the literature, as for example [4], see also [1].

The following assumptions are required:

1. The nonlinear term $\Phi(x)$ is Lipschitz, i.e. $\|\Phi(x_1)-\Phi(x_2)\| \le \ell \|x_1 - x_2\|$, where ℓ is the Lipschitz constant.
2. (A, C) is observable.

In order to design a fault detection observer the nominal (f=0) model should be used. Consider the next Thau type observer for the system (1):

$$\dot{\hat{x}} = A\hat{x} + Bu + \Phi(\hat{x}) + L(y - C\hat{x}) \tag{2}$$

The observation error dynamic results in

$$\dot{\tilde{x}} = (A - LC)\tilde{x} + \Phi(x) - \Phi(\hat{x}) \tag{3}$$

where $\tilde{x}(t) = x(t) - \hat{x}(t)$, and the time dependence is omitted by simplicity.

Sufficient conditions for the convergence of the estimation error to zero are guaranteed by theorem 1.

Theorem 1 [8]. *If a matrix* **L** *can be assigned such that*

$$(A - LC)^T P + P(A - LC) + \ell^2 PP + I < 0 \tag{4}$$

for some definite positive symmetric matrix **P**, *then this choice of* **L** *leads to asymptotically stable estimates by the observer (9) of the system (1).*

Remark 1 *As shown by [8], the inequality (4) can be rewritten as a linear matrix inequality as follows*

$$\begin{bmatrix} A^T P - C^T X^T + PA - XC + I & P \\ P & \frac{1}{\ell^2} I \end{bmatrix} < 0 \tag{5}$$

with P>0, X=PL. Equation (5) can be solved using standard convex optimization techniques, if the associated Riccati inequality has a feasible solution.

Remark 2 *The observer rate of convergence can be included in the design [8] by modifying the equation (5) as follows:*

$$\begin{bmatrix} A^T P - C^T X^T + PA - XC + I + \rho P & P \\ P & \frac{1}{\ell^2} I \end{bmatrix} < 0 \tag{6}$$

with $\rho > 0$.

A drawback of the considered approach is that if the Lipschitz constant is selected very big (conservative), the observer will be (if it exists) very robust but of little sensitivity to faults.

IV. MODEL OF A TWO WINDING SINGLE-PHASE TRANSFORMER

The kind of power transformers considered in this paper are single phase two winding. The corresponding linear model is well known in the literature [6] and recently a nonlinear version of this has been proposed [3].

In order to obtain the mathematical representation of the single phase transformer model, the equivalent circuit is used. The core losses are included through an appropriate resistance. A schematic representation could be found in Fig 2,

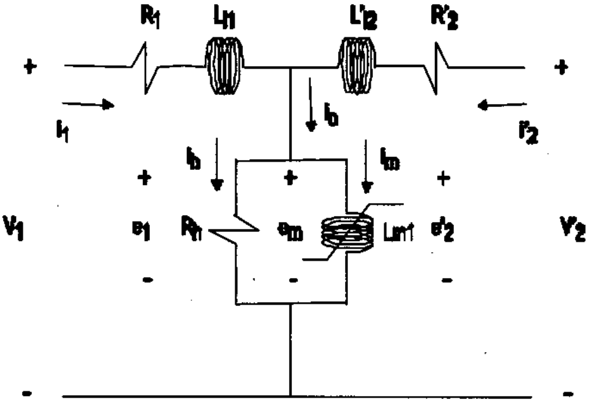

Fig.. 2 Equivalent circuit of a two-winding transformer

where R_h represents the hysteresis losses and L_{m1} represents the nonlinear inductance. It includes the saturation characteristics.

Consider the following assignation of the state variables: $x_1 = i_1$, $x_2 = i_2'$ and $x_3 = i_m$. The state space representation of the system is given by:

$$\begin{aligned} \dot{x} &= Ax + Bu + \Phi(x) \\ y &= Cx \end{aligned} \tag{7}$$

The corresponding matrices for the different cases are as follows:

- **Case 1**: without load

$$A=\begin{bmatrix}-\frac{R_1+R_h}{L_{l1}} & \frac{R_h}{L_{l1}}\\ \frac{R_h}{\alpha\beta} & -\frac{R_h}{\alpha\beta}\end{bmatrix}\quad B=\begin{bmatrix}-\frac{1}{L_{l1}}\\ 0\end{bmatrix}$$

$$C=\begin{bmatrix}1 & 0 & 0\\ R_h & 0 & -R_h\end{bmatrix}$$

- **Case 2: with resistive load.** If transformer is loaded with a pure resistance:

$$v_2'=-R_L i_2' \tag{8}$$

The system matrices are:

$$A=\begin{bmatrix}-\frac{R_1+R_h}{L_{l1}} & -\frac{R_h}{L_{l1}} & \frac{R_h}{L_{l1}}\\ -\frac{R_h}{L_{l2}'} & -\frac{(R_2'+R_h+R_L)}{L_{l2}'} & \frac{R_h}{L_{l2}'}\\ \frac{R_h}{\alpha\beta} & \frac{R_h}{\alpha\beta} & -\frac{R_h}{\alpha\beta}\end{bmatrix}$$

$$B=\begin{bmatrix}-\frac{1}{L_{l1}}\\ 0\\ 0\end{bmatrix}$$

$$C=\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\end{bmatrix}$$

The nonlinearity vector Φ is the same in both cases:

$$\Phi(x)=\begin{bmatrix}0\\ 0\\ \frac{\beta R_h}{\alpha}(x_1x_3^2+x_2x_3^2-x_3^3)\end{bmatrix}$$

The parameters α and β correspond to the fitting of saturation curve in the transformer. They could be calculated as in [7].

V. DETECTION OF INTERNAL FAULTS

Internal faults in the transformer include turn to turn faults as well as turn to earth ones. These kinds of faults are represented in Fig. 3.

Note that when a kind of these faults occurs, the model orders changes. This is important when fault isolation is required.

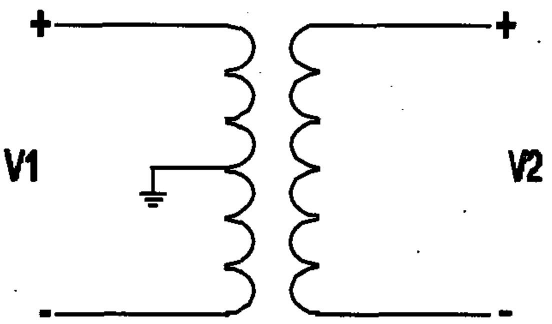

Fig. 3. Internal faults: turn to earth

VI. DESIGN OF THE FAULT DETECTOR

The design of the residual generator is based on the nominal (fault free) model of the system (7)

Case 1:

Note that in this case the current in the secondary of the transformer is zero (because no load is present). A consequence of this fact is that the nonlinear function $\Phi(x)$ could be obtained as a function of the system output (actually the measurements i_1 and v_2'), i.e. $i_1=y_1=x_1$, $i_2=0=x_2$ and $x_3=y_1-\frac{y_2}{R_h}$. With this the nonlinearity becomes $\Phi(x)-\Phi(y)$. The kind of observer required is:

$$\dot{\hat{x}}=A\hat{x}+Bu+\Phi(y)+L(y-C\hat{x}) \tag{9}$$

where the matrix L is designed as in the Luenberger observer [8]. The poles are selected to be on the left of the poles of the system matrix A.

Case 2:

Here the state of the system with load could not be recover from the output, and it means the no linearity should be considered as in section 2. Note that the known states (i_1 and i_2') could be incorporate and only the no measured state x_3 should be substituted in the observer by the estimated one ($\hat{x}_3$). The design of the observer follows the steps given in section 2.

VII. RESULTADOS

A turn to earth fault in the primary has been considered to test the designed residuals. The fault occurs at $t = 0.004$ *sec.* The input-output information has been generated using a simulation model. The fault was simulated using a three winding transformer model. The fault free system is a two-winding transformer. When a fault appear, the model is switching from two to three winding model. In order to simplify the simulation we use a three winding model, with the appropriate voltage selection, also for the fault free case. This is not represent the reality, as can be seen in the results (the residuals are not exactly zero in the fault free case), however for our test, it represent a worst situation test for the residuals.

Case 1: The residuals for the no loaded case can be found in Fig. 4 and Fig. 5. As can be seen the fault could be detected very well using the residual generated by the current i_1. On the other hand, the residual generated based on the voltage in the secondary v_2' could be used also or the detection task.

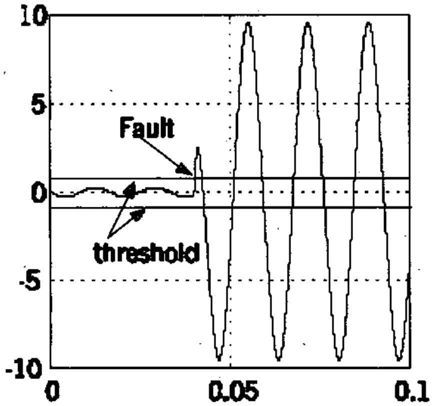

Fig. 4. Residual for primary current with a fault at 0.04 sec., case 1

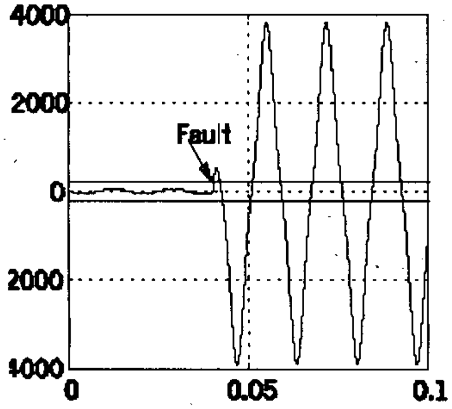

Fig. 5. Residual for secondary voltage with a fault at 0.04 sec., case 1

In both cases the threshold has been selected by a visual form (without an analysis), but in order to obtain a good detection time more work for the selection of the threshold should be realized.

Case 2: In this case two residuals are also available. The first one could be found in Fig. (6). As can be seen; the detection of the fault in the primary follows directly. The threshold should be assigned in order to avoid false alarms.

For the second residual, the fault is not well reflected on the residual, see Fig. 7 Note that this result is not surprising, because of the magnetic isolation between primary and secondary of the transformer.

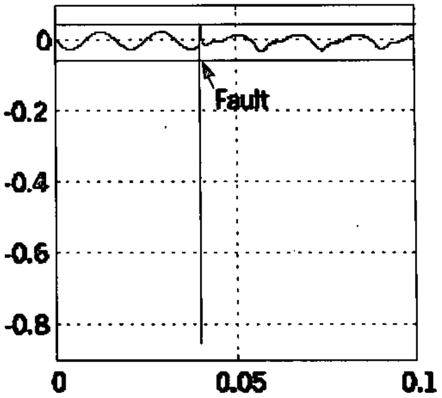

Fig. 6. Residual for primary current with a fault at 0.04 sec., case 2.

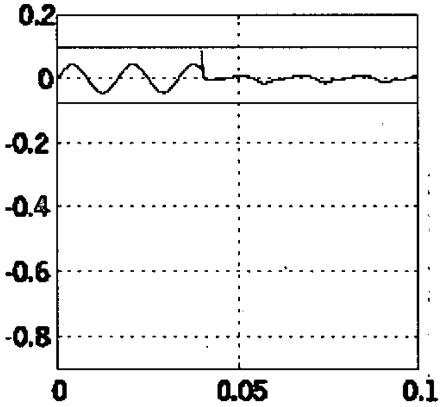

Fig. 7. Residual for current in the secondary with a fault at 0.04 sec., case 2.

VIII. CONCLUSIONS

In this paper a novel approach for the detection of internal faults in the transformer has been presented. The classical approach to do this task is the differential protection, however, in some cases this approach fails to detect faults. The proposed approach is based on the mathematical model of the transformer. Using an observer-based method, it is shown the detection of internal faults in the transformer could be carried out fast and safety. False alarms are reduced by the implementation of a threshold. A trade off between false alarms and sensibility should be studied in the future. Based on simulations, promisory results have been presented.

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X. BIOGRAPHIES

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