Proceedings of the Sixth IASTED International Conference
EUROPEAN POWER AND ENERGY SYSTEMS
June 26–28, 2006, Rhodes, Greece

AUTOREGRESSIVE MODEL-BASED COMPENSATION METHOD FOR THE SATURATED SECONDARY CURRENT OF A CURRENT TRANSFORMER

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ABSTRACT
Current transformer (CT) saturation may cause the mal-operation or operating time delay of protection relays. The secondary current can be expressed as the linear combination of sinusoidal and exponential signals, if no saturation occurs. In this paper, an advanced algorithm for the compensation of the distorted secondary current due to CT saturation is proposed. At first, the 3rd difference function detects the start and end of saturation in real-time. Secondly, the autoregressive model-based FIR filter and the least mean square curve fitting method are used to estimate the exponential component and the sinusoidal component. During saturated periods, the proposed algorithm estimates the unsaturated secondary current which is equal to the scaled primary current. Test results indicate that the proposed algorithm compensates the distorted currents accurately under a variety of fault conditions.

KEY WORDS
CT Saturation, Real Time Compensation, Auto Regressive Model

1. Introduction

CT saturation causes the distortion of the secondary current and some problems from the protection's point of view. During the saturation periods, a protection relay is unable to collect the correct information showing how the primary power system has changed. Consequently, the current distortion may cause the mal-operation or operating time delay of protective relays. A rule of thumb frequently used in relay engineering to minimize the CT saturation effects is choosing a CT having the voltage rating at least twice that required for the maximum steady-state symmetrical fault current [1]. The possibility of saturation, however, still exists because of the dc component of an asymmetrical fault current and the remanent flux in a CT core.

Several techniques on the compensation of the distorted secondary current have been published. An algorithm to estimate the magnetizing current at each time step by using the magnetization curve of a CT was reported in [2]. The technique is valid in various systems and fault conditions, but relies on the assumption that the remanent flux was zero before the fault. To cope with the drawback of the algorithm in [2], an algorithm in [3] is suggested for calculating the core flux when the CT enters saturation. A compensation method by estimating the exciting current was suggested in [4] to improve the accuracy of a measurement CT. The technique assumes that the primary current is sinusoidal without dc component. In addition, the algorithms in [3] and [4] require CT parameters/ characteristics.

An ANN based approach for correcting the distorted secondary current was reported in [5]. The ANN was trained to provide the inverse function of the CT. However, the effect of remanent flux was not considered.

The other algorithm [6] detects the saturation using the Discrete Wavelet Transform (DWT) and compensates the distorted section of a secondary current with features extracted from the healthy section using a least mean square fitting method. The suggested algorithm in [7] only uses a least mean square fitting method without a saturation detection technique. However, these methods needs time delay for compensation because [6] uses the first turning point after the distortion to determine the initial phase angle of a fault current and [7] uses the second unsaturated section. A compensating method using AR model was suggested in [8]. The method needs a certain number of samples before the first saturation to calculate the AR coefficients. If there are not enough samples before saturation because of a deep saturation, the compensated current may contain significant errors.

In this paper, to cope with the drawback of the algorithm in [8], an advanced method is suggested. The algorithm based on the 3rd difference function in [9] is used to detect the start and end of saturation in real-time. The FIR filter based on autoregressive model and the least mean square curve fitting method are used to estimate the exponential component and the sinusoidal component form the healthy section. During saturation periods, the proposed algorithm compensates the distorted current signal by using the estimated components; when the CT leaves saturation period, the algorithm does not compensate the current. The performance of the proposed algorithm is verified under various conditions including the remanent flux in the core using EMTP.

2. Advanced Compensation Algorithm

2.1 Estimation of the DC component using AR model

The fault current flowing through the primary circuit can be considered as the superimposition of an exponential component(x_0) and a sine component(x_1), given as

$$i(t) = x_0(t) + x_1(t) = C_0 e^{-t/\tau} + C_1 \sin(wt + \varphi_1) \quad (1)$$

where τ and C_0 are the time constant and the amplitude of the exponential component, C_1 and φ_1 are the amplitude and the phase angle of the sine component, and w is the fundamental angular frequency of the current signal. The fault current sampled at times t-Δt and t+Δt can be expressed as

$$i(t-\Delta t) = x_0(t-\Delta t) + x_1(t-\Delta t) \quad (2)$$

$$i(t+\Delta t) = x_0(t+\Delta t) + x_1(t+\Delta t) \quad (3)$$

where Δt is the sampling interval. Using the AR model in [6], the sine component of (3) can be rewritten as

$$x_1(t+\Delta t) = (2-(w\Delta t)^2)x_1(t) - x_1(t-\Delta t) \quad (4)$$

Substituting $x_1(t+\Delta t)$ of (4) into (3) yields

$$i(t+\Delta t) = x_0(t+\Delta t) + (2-(w\Delta t)^2)x_1(t) - x_1(t-\Delta t) \quad (5)$$

By substituting $x_1(t)$ of (1) and $x_1(t$-$\Delta t)$ of (2) into (4) and rearranging, we can obtain a FIR filter for estimating the exponential component as follows

$$\begin{aligned} y_{AR}(t) &= i(t+\Delta t) - (2-(w\Delta t)^2)i(t) + i(t-\Delta t) \\ &= x_0(t+\Delta t) - (2-(w\Delta t)^2)x_0(t) + x_0(t-\Delta t) \\ &= C_0 e^{-(t+\Delta t)/\tau} - (2-(w\Delta t)^2)C_0 e^{-t/\tau} + C_0 e^{-(t-\Delta t)/\tau} \\ &= C_0 e^{-t/\tau}(w^2 + 1/\tau^2)\Delta t^2 \end{aligned} \quad (6)$$

Then the exponential component($\hat{x}_0$) can be estimated by (7) and (8)

$$\frac{y_{AR}(t)}{y_{AR}(t+\Delta t)} = e^{\Delta t/\tau} \approx 1 + \frac{\Delta t}{\tau} + \frac{1}{2}\left(\frac{\Delta t}{\tau}\right)^2 \quad (7)$$

$$\hat{x}_0(t) = C_0 e^{-t/\tau} = \frac{y_{AR}(t)}{(w^2 + 1/\tau^2)\Delta t^2} \quad (8)$$

2.2 Estimation of the fundamental component

The fundamental component($\hat{x}_1$) can be obtained by eliminating the exponential component($\hat{x}_0$) from (1) as follows

$$\begin{aligned} \hat{x}_1(t) &= i(t) - \hat{x}_0(t) \\ &= C_1 \sin(wt + \varphi_1) \\ &= C_1 \sin(wt)\cos(\varphi_1) + C_1 \cos(wt)\sin(\varphi_1) \end{aligned} \quad (9)$$

At time t_1, (9) can be rewritten in the more convenient form

$$\hat{x}_1(t_1) = a_{11}u_1 + a_{12}u_2 \quad (10)$$

$$\text{where } a_{11} = \cos(wt_1),\ a_{12} = \sin(wt_1)$$
$$u_1 = C_1\cos(\varphi_1),\quad u_2 = C_1 \sin(\varphi_1)$$

Note that the a-coefficients in (10) only depends on t_1. The unknown variables, u, will be identified by using a least square fitting method.

2.3 Compensation algorithm for the distorted secondary current

To detect the start and end of saturation in real-time, the algorithm based on the 3rd difference function in [7] is used.

The AR model-based FIR filter is used to estimate and to eliminate the exponential component from the measured secondary current during unsaturated periods. Although an actual fault current includes harmonic components, they are not considered as the input of the FIR filter. Therefore, the FIR filter produces some errors due to harmonic components. In this paper, a 5-point moving average filter is used for reducing the adverse effect of harmonic components and then the least square curve fitting method is used for estimating the sinusoidal component.

During saturated periods, the proposed algorithm compensates the distorted current signal by using the estimated exponential and fundamental components.

3. Case Studies

3.1 Power System Configuration

The performance of the algorithm was evaluated for various faults on a 345 kV, 100 km simple overhead transmission line, as shown in Fig. 1. The simulated fault cases involve single phase-to-ground faults located at 2 km from S bus. The sampling frequency was set to 3,840 Hz i.e. 64 samples per cycle in 60Hz systems, and the remanent flux in a CT ranged from -80 % to 80 %.

The CT modeling described in [10] was used to simulate the remanent flux. A resistive burden of 8.04 Ω was connected to a C800 CT (2000:5). The saturation point of (2.60 A, 3.370 Vs) is selected to generate hysteresis data using HYSDAT, an auxiliary program in EMTP.

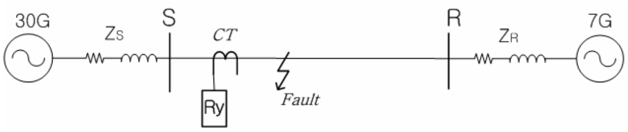

Fig. 1. Single line diagram of the model system

As a performance index, the transient error in [11] is calculated as

$$\text{transient error} = \frac{K_n \cdot i_2(t) - i_1(t)}{\sqrt{2} \cdot I_{psc}} \times 100 \ (\%) \qquad (11)$$

where I_{psc} is the rated primary short-circuit current and K_n is the turns ratio of the CT.

3.2 Test Results

A. Estimation of the AR coefficients using a least square fitting method in [8]

The algorithm in [8] used the 5th order AR model; the fault current modeled as a linear combination of the dc-offset, power frequency component, and a harmonic component. This algorithm needs a certain number of samples before the first saturation to calculate the coefficients. If the 5th order AR model is to be used, 5+α samples should be required, where α is the number of samples for the least square fitting. If there are not enough samples before saturation because of a deep saturation, the transient error can be magnified as shown in Fig. 2. In the first graph, the dotted and solid lines show the scaled primary and measured secondary currents, respectively. In the second one, the dotted and solid lines show the scaled primary and compensated secondary currents, respectively. The last one shows the transient error of the algorithm.

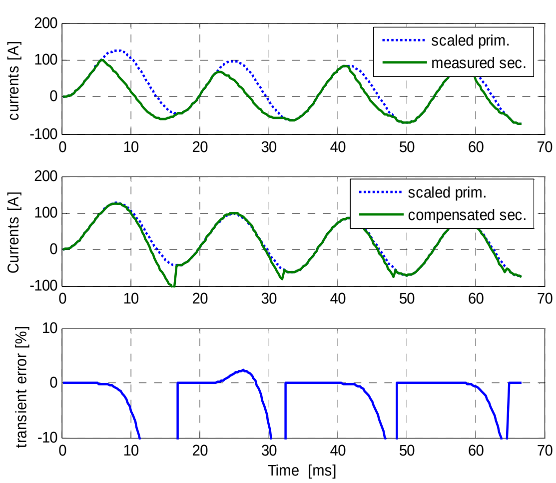

Fig. 2. Compensation result using the method in [8] (remanent flux +40%)

B. Least Mean Square (LMS) fitting with the FIR filter based on AR model

Remanent flux affects the start and duration of CT saturation. The dc component has far more influence on the saturation than the magnitude of the sine component in a fault current. Therefore, the proposed algorithm was tested at remanent flux levels varying from -80% to +80% of the saturation point.

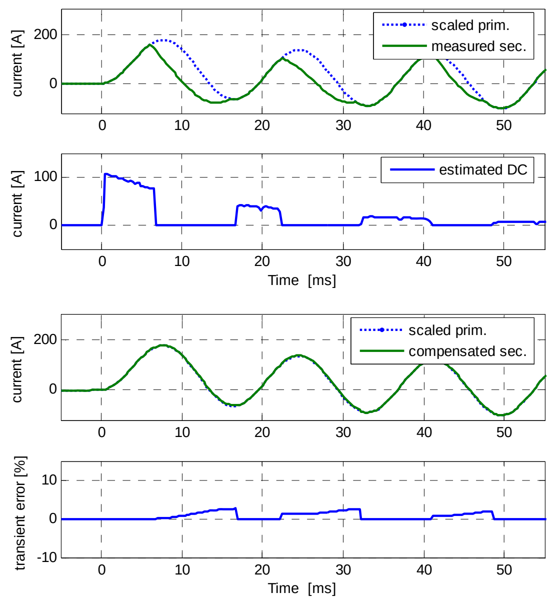

Fig. 3. Compensation result using LMS with the AR model (remanent flux 0%)

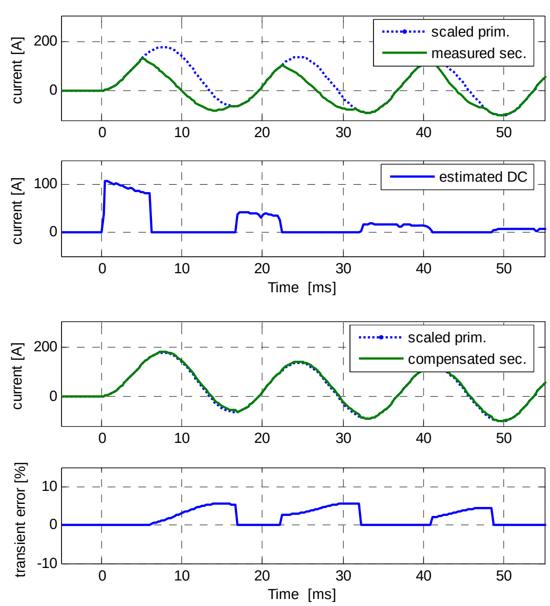

Fig. 4. Compensation result using LMS with the AR model (remanent flux +80%)

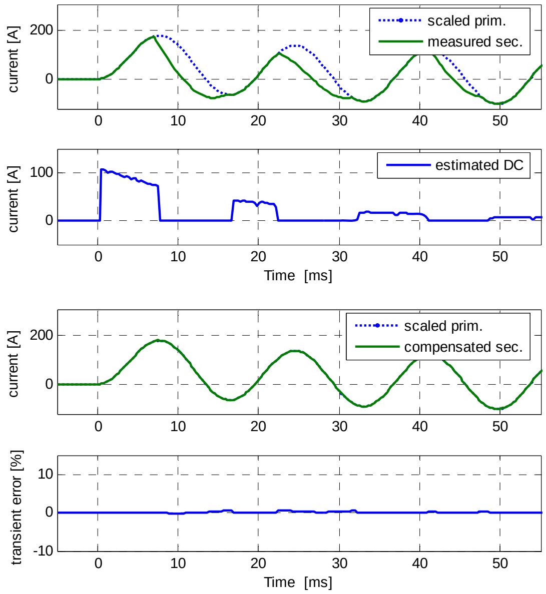

Fig. 5. Compensation result using LMS with the AR model (remanent flux -80%)

In Fig. 3 to Fig. 5, some compensation results using the proposed method are demonstrated for three fault cases. The second graph in each figure shows the estimated exponential component by the AR model-based FIR filter. Table I summarizes the maximum transient error in each case with different remanent flux. The maximum error is less than 5.3 % in all cases. The results indicate that the proposed algorithm can accurately estimate secondary current although a CT is deeply saturated by the remanent flux and the large dc component in the fault current.

TABLE I
Variation of the maximum transient error with the remanent flux

Fault distance is 0.02 pu, fault inception angle is 0°					
Remanent flux [%]	-80	-40	0	40	80
Max. error [%]	0.66	1.76	2.64	0.88	5.64

Table II shows the effect of the fault distance on the estimation error and indicates that the performance of the proposed algorithm is not significantly affected by the fault distance.

TABLE II
Variation of the maximum transient error with the fault distance

Remanent flux 80 %, Fault inception angle 0°				
Fault distance [pu]	0.02	0.05	0.10	0.15
Max. error [%]	5.64	1.65	3.40	1.42

4. Conclusion

In this paper, an advanced algorithm for the compensation of the distorted signal due to CT saturation is proposed. The algorithm first utilizes the 3rd difference function for detecting the start and end of saturation in real-time. Secondly, the AR model-based FIR filter and the least mean square curve fitting method are used to estimate the exponential component and the sinusoidal component from the unsaturated periods. During the saturated periods, the proposed algorithm compensates the distorted current signal by using the estimated components. This method uses only the collected current data without any parameters of a CT. Simulation results indicated that the proposed algorithm compensates the distorted current with a high accuracy. The algorithm shows very stable features under various fault conditions even though a CT is deeply saturated with a large remanent flux.

Acknowledgements

This work was supported by the ERC program of MOST/KOSEF (Next-generation Power Technology Center)

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