Application of Kalman filter for prevention of unrequired operation of power transformer differential protection

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Abstract. As power transformers are core elements of electric power supply systems, transformer protection systems must reach high requirements. In order to reduce possible damage to transformers and prevent cases of false operations, resulting in interruptions of technological processes, protection devises with high sensitivity and high speed are required. This paper represents implementation of Kaman filtering theory with reduced calculation time for identification of faults in transformer from other transients. Parameters for tuning of Kalman filter for protection task and identification criteria were established. Operation of proposed algorithm was experimentally compared to Fourier transform based algorithm.

1. Introduction
Power transformers are core elements of power supply systems and their reliability determines reliability of electric power supply and steadiness of technological processes. In order to prevent internal faults in transformers, differential relay protection, based on comparison of currents on the transformer input and output, is used. One of the tasks of relay protection is the quickest possible location of the fault and disconnection of transformer in order to reduce possible damage and repair costs. This task is complicated by possible transients in electric grid, such as switching of electric load or external short-circuit failures, which could cause unrequired operation of power transformer differential protection [1,2].

Blocking and restraining algorithms are used in modern blocking relay protection devices for prevention of unrequired operations. Control of definitive characteristics of fault and nonfault signals of transformer protection devices is used in order to implement those algorithms. Algorithms based on signal spectral analysis are the most universal of these [3,4,5].

Calculation of percentage composition of harmonics in differential current requires specific time, therefore operation or blocking of differential relay protection is delayed by this time, generally exceeding one period of system voltage. In order to reduce calculation time it is feasible to consider usage of Kalman optimal filtering theory based algorithms. This algorithm allows reduction of spectral analysis calculation time by means of a priori information about process [6,7].

2. Implementation of Kalman filtering
Kalman filters are used for optimal filtering of discrete time signals \( t_k = kT_d \), there \( T_d \) – sampling period. Effectiveness of algorithm is achieved by availability of preliminary information about process with consequent improvement of estimation by comparison of estimated values to indirect measurement results [8]. Structure of Kalman filter is represented in figure 1.
Signals of relay protection are described by Kalman filtering theory terminology, which uses transition model of process in a form of constitutive equations in relation to $x_k = x(t_k)$ state vector and observation (measurement) model, connecting state vector $x_k$ and measurement vector $z_k$:

$$x_{k+1} = Ax_k + w_k, \quad z_k = Hx_k + v_k.$$  (1)

Here $A$ – state-transition matrix, $H$ – observation matrix, $w_k = N(0,W_k)$ – vector of white noise with zero expected value $<w_k>=0$ and covariance matrix covariance matrix $W_k = <w_kw_k^T>$, $v_k = (0,V_k)$ – vector of measurement white noise.

Stochastic processes $w_k$ and $v_k$ are independent from each other, estimation accuracy $\hat{x}_k$ of process $x_k$ is described by covariance matrix $P_k = <e_ke_k^T>$, there $e_k = x - \hat{x}_k$ – vector of estimation error. Filter provides optimal estimation of signals in criteria of minimal estimation error module.

In order to form model in a state space in accordance with (1), differential protection currents for various operating modes of transformer were studied. Current spectrum for transformer inrush has spikes at zero, main and second harmonic frequencies, while internal fault current spectrum has spikes only for zero and main harmonics. For the case of transformer overexcitation, current spectrum has odd harmonics, from those fifth harmonic has the most value. Therefore model of measured signal in a state space must include main, second and fifth harmonics with random amplitude and phase, as well as exponentially decaying aperiodic component with random initial value:

$$z(k\Delta t) = I_1 \cos(\omega_0 k\Delta t + \varphi_1) + I_2 \cos(2\omega_0 k\Delta t + \varphi_2) + I_5 \cos(2\omega_0 k\Delta t + \varphi_5) + I_0 e^{-\frac{k\Delta t}{\lambda}},$$  (2)

Here $z$ – model of measured signal; $I_1, I_2, I_5$ – amplitudes of main, second and fifth harmonics; $\varphi_1, \varphi_2$ – phases of main, second and fifth harmonics; $\omega_0 = 2\pi f_0$ – frequency of main harmonic; $I_0$ – initial value of aperiodic component; $\lambda$ – time response of aperiodic component; $\Delta t$ – sampling period of filter.

In order to form state-transition matrix $A$, periodical part of discrete time signal is described with projections $x_n[k]$ and $x_m[k]$ of complex vector $X_{ma} \exp[ j(\Theta_n k + \varphi_n)]$ on a real and imaginary axis. Sub matrix of state-transition matrix $A_n$ for n-harmonic is calculated considering

$$x_n[k+1] = x_n[k] \cos \Theta_n - x_m[k] \sin \Theta_n$$ and $x_m[k+1] = x_n[k] \cos \Theta_n + x_m[k] \sin \Theta_n$ as:

![Figure 1. Structure of Kalman filter in Simulink MATLAB.](image-url)
\[
\begin{bmatrix}
    x_{n+1} \\
    x_{n,n+1} \end{bmatrix} = A_n \cdot \begin{bmatrix}
    x_{n} \\
    x_{n,n} \end{bmatrix}, \quad A_n = \begin{bmatrix}
    \cos \Theta_n & -\sin \Theta_n \\
    \cos \Theta_n & \sin \Theta_n \end{bmatrix}.
\]

(3)

Using equation for aperiodic component \(i_s[k+1] = I_o \exp(-T_o / \tau) \cdot i_s[k] \), state-transition matrix \(A\) is calculated from submatrices \(A_n\) as:

\[
A = \text{diag}[A_1, A_2, \ldots, A_n, I_o \exp(-T_o / \tau)].
\]

Observation matrix is formed as \(H = [1,0,1,0,1,0,1]\).

Three Kalman filters are used for estimation of differential protection currents, one for each of the phases. Restriction function for blocking of three-phase transformer protection is calculated by summing of harmonics of all three phases. Squares of main, second and fifth harmonics are calculated in accordance with:

\[
\begin{align*}
I_{1k}^2(3) &= Ia_{1k}^2 + Ib_{1k}^2 + Ic_{1k}^2, \\
I_{2k}^2(3) &= Ia_{2k}^2 + Ib_{2k}^2 + Ic_{2k}^2, \\
I_{5k}^2(3) &= Ia_{5k}^2 + Ib_{5k}^2 + Ic_{5k}^2.
\end{align*}
\]

(5)

Studies [9] show, what for inrush currents second harmonic is always higher than 30% of main harmonic. Therefore protection algorithm was tuned for operation if second harmonic is lower than 20% of main harmonic. Otherwise protection system operation is blocked. This condition can be described as \(I_2/I_1 < 0.2\) or \(I_2^2 < 0.04I_1^2\). For transformer overexcitation, fifth harmonic is not lower than 18% of main harmonic. Therefore protection was tuned for operation if fifth harmonic is lower than 12% of main harmonic and is blocked otherwise. This can be described as \(I_5/I_1 < 0.12\) or \(I_5^2 < 0.0144I_1^2\).

In order to reduce influence of dispersion and variability of percentage composition of second and fifth harmonics by transformer phases, protection system uses cross-blocking algorithm. Protection system operation is blocked if for any of three Kalman filters second harmonic exceeds ratio \(F_2 = I_{2m}^2 / I_{1m}^2 > D_2 = 0.05\) or fifth harmonic exceeds ratio \(F_5 = I_{5m}^2 / I_{1m}^2 > D_5 = 0.04\).

3. Validation of algorithm

For validation of proposed algorithm, physical model of transformer in distribution grid was used. Algorithm was tested for various transients, including internal short circuits, transformer inrush, external fault and input voltage surge. Calculation speed of Kalman filter was tested for transformer inrush transient as a time when parameter \(F_2\) reaches setting value \(D_2 = 0.05\). If parameter value \(F_2\) exceeds setting value \(F_2 > D_2\), algorithm forms command for blocking of relay protection system operation. Then parameter \(F_2\) reaches setting value \(F_2 < D_2\), blocking command is canceled.

Kalman filter algorithm was compared to Fourier spectral analysis algorithm, which is commonly used in modern digital relay protection systems. Fourier spectral analysis algorithm was implemented as program in Simulink MATLAB software.

Dynamics of operation criteria \(F_2\) for the cases of internal fault and transformer inrush is presented in figure 2. Graph 1 represents Kalman filter, graph 2 represents Fourier algorithm. Setting value \(D_2 = 0.05\) is represented by the line, dividing area of blocking and area of operation for protection system. Point where graphs 1 and 2 cross line 3 is a time of fault detection \(t_K\) and \(t_o\) for Kalman and Fourier algorithms respectively.
Figure 2. Operation of Kalman and Fourier based algorithms in cases of transformer internal fault (a) and transformer inrush (b).

As shown in figure 2a time of detection of internal fault by Kalman filter is \( t_K = 6 \) ms, while for Fourier algorithm it is \( t_F = 16 \) ms. In case of transformer inrush (figure 2b) parameter value \( F_2 \) exceeds setting value \( D_2 = 0.05 \) for whole time of calculation for both Kalman and Fourier based algorithms.

4. Conclusion
As it is shown by experiment, proposed algorithm has higher speed of fault detection compared to Fourier based protection algorithms. Time of calculation for Kalman filter is lower than half of supply voltage period, which corresponds with calculation times of high speed protection algorithms. Therefore implementation of Kalman filter for differential relay protection systems as blocking algorithm is efficient, as reduced time of spectral analysis provides faster operation of protection systems with the same level of reliability.
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