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New Variable Window Adaptive Distance Protection for Tee'd Feeders

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***Abstract*--The new enhanced protection method dedicated for HV three-ended transmission lines is presented. Estimation of the fault location based on orthogonal components of voltages and currents calculated by use of developing window filters is discussed. The core contribution lies in introduction of variable reach characteristics of distance protection that are coordinated with proposed expanding data window filters. The performance of the scheme was tested with use of data obtained from EMTP-ATP simulations of faults in an HV test power network.**

***Index Terms*--adaptive reach, distance protection, tee'd feeder variable window filters**

I. Introduction

ONE of the best solutions for reliable and fast HV line protection is the application of differential principle. However, to implement it, dedicated high-speed data transmission channels are required. Information on currents from opposite terminals has to be transmitted every sampling period. Moreover, the sampling process must be synchronized [1].

The other solution widely used for transmission line protection is application of distance relays. However, its use for three-terminal circuits is much more difficult than for two-terminal lines. It is well known that it requires careful consideration and check of all conditions such as infeeds from both opposite terminals, effect of pre-fault load as well as influence of the fault current flowing outwards at one terminal [2, 3]. For the sample transmission circuit from Fig. 1 the fault loop impedance measured at terminal A (provided that local voltages and currents are available only) can be expressed by the equation

$$Z_A = Z_{LA} + Z_{LB} + \frac{I_C}{I_A} Z_{LB} \tag{1}$$

which shows penchant for overestimation of impedance approach (last term of (1) represents impedance estimation error resulting from uncompensated current infeed).

To mitigate these difficulties methods based on new ideas should be applied for protection of tee'd feeders. An improved distance principle supplemented by directional triggering is suggested in [4]. Adaptation of distance relays settings for multi-terminal lines employing agent technology is proposed in [5]. In this paper an approach based on fault location algorithm [6] and variable window filters is discussed.

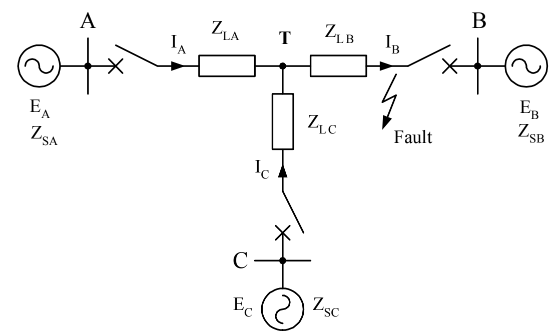

Fig. 1. Three-terminal transmission system.

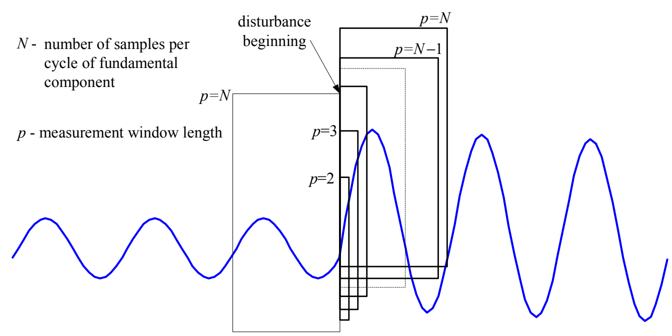

Fig. 2. Illustration of the expanding data window.

The presented herein distance approach can be applied under assumption that all impedances in the system from Fig. 1 are given, local processing of phase voltages and currents is performed as well as remote information on pre-fault currents magnitudes from opposite terminals is available. The frequency of information updating from opposite terminals is to be defined based on expected changeability of the signals.

The developed new protection concept is described in Section II. The estimation of orthogonal components of protective signals based on variable data window filtering is proposed to improve performance of the impedance algorithm for faults in Zone 1. The fault location-like distance calculation algorithm is also presented. The performance of the proposed scheme is discussed in Section III. Thorough study of transients measured using variable window filters led to the new strategy of their data window expansion. An idea of variable reach of the Zone 1 is also described.

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II. New Protection Concept

A. Variable window filtering procedure

Full cycle filters (usually the Fourier ones) are commonly used in most digital protection relays. Their advantages in frequency domain are yet paid off by rather slow time response; thus variable window solutions seem to constitute a promising alternative [7]. Assuming that the fault inception time (generally any moment of sudden signal change) is known, the filtering procedure is started with possibly shortest (two-sample) window, that is further successively expanded until it reaches full cycle of the fundamental frequency (Fig. 2).

The coefficients of adaptable filters (sine/cosine ones) can be calculated from formulas:

$$
\begin{aligned}
a_k^d &= \frac{\sin\left[\frac{2\pi}{N}\left(k-\frac{p+1}{2}\right)\right]}{\sum_{i=1}^{p}\sin^2\left[\frac{2\pi}{N}\left(i-\frac{p+1}{2}\right)\right]} \\
a_k^q &= \frac{\cos\left[\frac{2\pi}{N}\left(k-\frac{p+1}{2}\right)\right]-\frac{1}{p}F(p)}{\sum_{i=1}^{p}\cos^2\left[\frac{2\pi}{N}\left(i-\frac{p+1}{2}\right)\right]-\frac{1}{p}\left(F(p)\right)^2} \qquad (2) \\
F(p) &= \sum_{i=1}^{p}\cos\left[\frac{2\pi}{N}\left(i-\frac{p+1}{2}\right)\right] \\
k &= 1,\ldots,p;\ \ p=1,2,\ldots,N
\end{aligned}
$$

where p is the window length and N is the number of samples per cycle of the fundamental component. Since filtering with cosine filter for $p<N$ does not fully suppress DC component, the coefficients of this filter are corrected by adding constant offset for given p. For $p \geq N$ the filtering with variable data window becomes conventional filtering with fixed data window [7].

Expanding data window filtering procedure is sensitive to higher harmonics in the currents and voltages to be processed, especially at the beginning of filtration, i.e. just after fault inception. The frequency characteristics of considered filters for various values of p, sampling rate 1kHz and power frequency 50Hz are shown in Fig. 3. One can notice that the filter gains for fundamental (power) frequency are equal 1.0 and the DC component is fully eliminated, irrespectively of p, while the attenuation of higher harmonics improves considerably when filter window length increases.

Thorough investigations on the dynamics of the distance to fault estimation process have revealed that there is still a need for modification of the fundamental approach based on variable data window, with sample-by-sample (SBS) window expanding. To remove transient discrepancies between impedance estimates and the actual fault location a new approach to signal processing based on the variable data window length is proposed in this paper. The scheme of the new procedure is shown in Fig. 4. The filtration based on full data window length is continued up to 3 samples after fault inception. As the next three new fault samples are being collected the process of adaptive window filtering starts with the window of 3 samples, spreading gradually to 7 samples. Then the window starts to move with the constant length until it reaches the 13th sample. Here the movement of the window is stopped and the length keeps expanding to 20 samples. In this way the constant length window is reached after 25 samples from fault inception (1¼ N, by sampling at 1kHz). The advantages of the new method of filter data window expansion are illustrated in Section III.

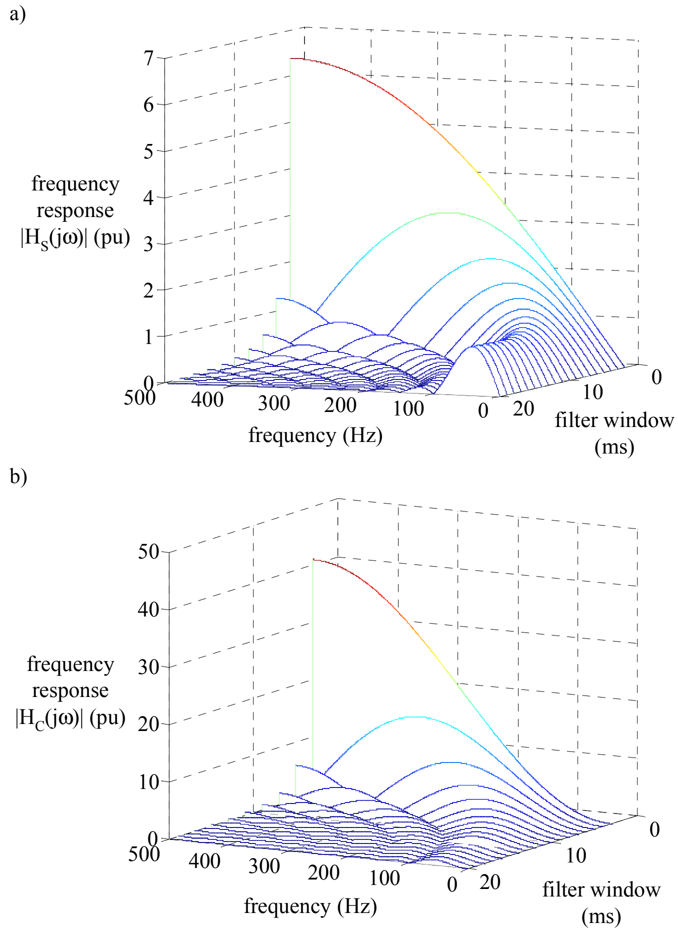

Fig. 3. Frequency characteristics of the expanding window filters: a) sine, b) cosine.

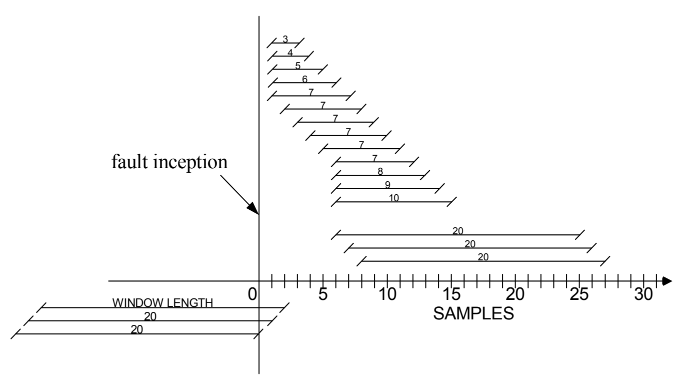

Fig. 4. New approach to filtering based on the variable data window length.

B. Fault distance estimation

In this paper it is proposed that the fault distance is to be determined with application of a fault location type algorithm (executed on-line). By analyses of appropriate fault loops for particular fault types (sequence schemes) adequate equations for estimating distance between terminal A and fault location may be developed [6]. In all cases the unknown distance *d* is a solution of the quadratic formula

$$a * d^2 + b * d + c = 0 \quad (3)$$

If the calculated distance *d*=0, then the fault is expected at the origin of the section T-B or T-C (T-point), while *d*=1 is recognized as fault at the end of the section considered.

The coefficients of (2) depend very much on the fault type that should be determined and are also related to the hypothetically faulted feeder. The detailed formulae are given here for the selected fault type only (L1-G) due to paper space shortage:

$$\begin{aligned} a &= \mathrm{Re}(AA2) * \mathrm{Im}(AR0) - \mathrm{Im}(AA2) * \mathrm{Re}(AR0) \\ b &= \mathrm{Re}(AA1) * \mathrm{Im}(AR0) - \mathrm{Im}(AA1) * \mathrm{Re}(AR0) \\ c &= \mathrm{Re}(AA0) * \mathrm{Im}(AR0) - \mathrm{Im}(AA0) * \mathrm{Re}(AR0) \end{aligned} \quad (4)$$

For single-line-to-ground faults in section T-B the coefficients have to be calculated as follows:

$$\begin{aligned} & AA2 = [I_0 Z_{0LB} Z_{1C} (Z_{0C} + Z_{0A}) / Z_{1LB} + I_1 Z_{0C} Z_{1C} + \\ & + I_2 Z_{0C} (Z_{1C} + Z_{1A}) + (I_{1C}^{pre\_e} Z_{1C} + Z_{1A} (I_1 - I_1^{pre})) Z_{0C}] Z_{1LB}^2 \\ & AA1 = \{ Z_{1C} [U_1 + I_1 (Z_{1LA} + Z_{1LB} - Z_{1SB})] + \\ & + I_2 (Z_{1C} + Z_{1A})(Z_{1SB} - Z_{1LB} - Z_{1AC}) + \\ & + (I_{1C}^{pre\_e} Z_{1C} + Z_{1A} (I_1 - I_1^{pre}))(Z_{1SB} - Z_{1LB})] \} Z_{1LB} Z_{0C} + \\ & + I_0 Z_{1C} (Z_{0C} + Z_{0A}) [Z_{0LB} (Z_{1SB} - Z_{1LB}) - Z_{0AC} Z_{1LB}] \\ & AA0 = I_0 Z_{1C} (Z_{0C} + Z_{0A})(Z_{0LB} Z_{1SB} + Z_{0AC} Z_{1SB}) + \\ & + Z_{0C} [U_1 Z_{1C} Z_{1SB} - I_1 Z_{1C} Z_{1SB} (Z_{1LA} + Z_{1LB}) - \\ & - I_2 (Z_{1C} + Z_{1A})(Z_{1LB} Z_{1SB} + Z_{1AC} Z_{1SB}) - \\ & - (I_{1C}^{pre} Z_{1C} + Z_{1A} (I_1 - I_1^{pre})) Z_{1LB} Z_{1SB}] \\ & AR0 = -3 \cdot I_2 Z_{0C} (Z_{1C} + Z_{1A}) \cdot (Z_{1B} + Z_{1AC}) \end{aligned} \quad (5)$$

where: $I_{0(1,2)}$, $U_{0(1,2)}$ – phasors of zero, positive and negative sequence currents and voltages, I_x^{pre} , $I_x^{pre\_e}$ – pre-fault and estimated pre-fault phasors of current in given section and for given component. For faults in section T-C indexes B ought to be replaced with C and vice versa.

The expressions for impedances from Fig. 1 connected in series and parallel (for given symmetrical components) are as follows

$$\begin{aligned} Z_{1(0)A(B)(C)} &= Z_{1(0)SA(B)(C)} + Z_{1(0)LA(B)(C)} \\ Z_{1(0)AC} &= Z_{1(0)A} \| Z_{1(0)C} \\ Z_{1(0)BC} &= Z_{1(0)B} \| Z_{1(0)C} \end{aligned} \quad (6)$$

Since the equation (3) is a quadratic one, its solutions are two distances $d_{1(2)}$. The selection of the correct value of fault distance is carried out in two steps. First of all the faulted section is detected when $0<d<1.05$. In case of either imaginary part $\mathrm{Im}(d)>0.05$, $\mathrm{Im}(d)<-0.05$ or negative *d* one or both distances are rejected. Value of *d* greater than 0.8 indicates forward faults outside of the zone Z1 in case of hypothetic faults in sections T-B or T-C (Zone1 assumed to reach 80% of both opposite lines irrespective of their lengths).

An additional criterion for selection of correct value of *d* is also the sign of the estimated fault resistance. The negative value of resistance calculated from the formula

$$R_{F1(2)} = \frac{-d_{1(2)}^2 \cdot \mathrm{Im}(AA2) - d_{1(2)} \cdot \mathrm{Im}(AA1) - \mathrm{Im}(AA0)}{\mathrm{Im}(AR0)} \quad (7)$$

should result in cancelling the hypothesis regarding given distance value *d*.

Further development of the distance scheme is related to the adaptive reach of the protection, which should be coordinated with dynamic features of proposed filtering procedure with expanding data window. The resulting dynamic settings of the relay (first zone reach) are outlined in next section of the paper, together with description of the scheme performance under fault conditions.

III. Performance of the Scheme and its Optimization

To analyze the performance of the new adaptive distance protection scheme and specify the adaptive protection reach, the model of a simple power system (as in Fig. 1, 110kV voltage level, line section lengths: A-T – 100km, T-B – 80km and T-C – 50km) has been prepared in EMTP standard [8]. Numerous fault cases have been simulated along particular line sections. The variables of simulation studies were:

- fault location (faults were staged at busbars of the terminals and every 5% of section length and also between 95% of section length and T point),
- fault resistance (R_F=1.0Ω or 10Ω for single- and double-line-to-ground faults and 0.1Ω or 1.0Ω in case of double- and three-phase faults).

In addition, for particular fault cases, angles of voltage sources at the ends B and C were being changed within the range of ±15% around −30° for feeder T-B and around −15° for feeder T-C.

A. Performance of the algorithm in transient states

The results of fault distance calculation with the variable window filtering and distance estimation procedure for sample single-phase-to-ground fault in the middle of the line section A-T are presented in Fig. 5. It is seen that the fault distance estimates obtained by use of the variable window filters converge much faster to the accurate value (*d*=0.5) than that attained with use of the full-cycle fixed-length window filters. The curve of fault distance calculated by use of the variable data window filters expanding as proposed in Fig. 4 exhibits lower transient errors and stabilizes faster than that obtained with traditional SBS expanding window filters.

The advantage of application of the orthogonalisation based on variable data window is noticeable only for the first 25 samples from fault inception. The estimates of fault distance converge faster compared to classical approach and after 25ms form the same diagrams.

The statistical picture of the variable window distance algorithm accuracy and convergence speed is presented in Fig. 6 for all fault types, whereas the curves represent the average underreach of the scheme at given time steps. The diagrams were prepared for a number of faults staged at 80-100% of the adjacent line sections (T-B, T-C) for both fixed and variable window measurement schemes. One can see that the scheme transient underreach (which may lead to possible false tripping) is the highest for faults involving ground, when the standard fixed window method is applied. With the optimized variable window measurement (DW changes according to Fig. 4) the fault distance estimation errors are greatly reduced and the advantage of proposed scheme is especially visible for double-line faults (Fig. 6b, c).

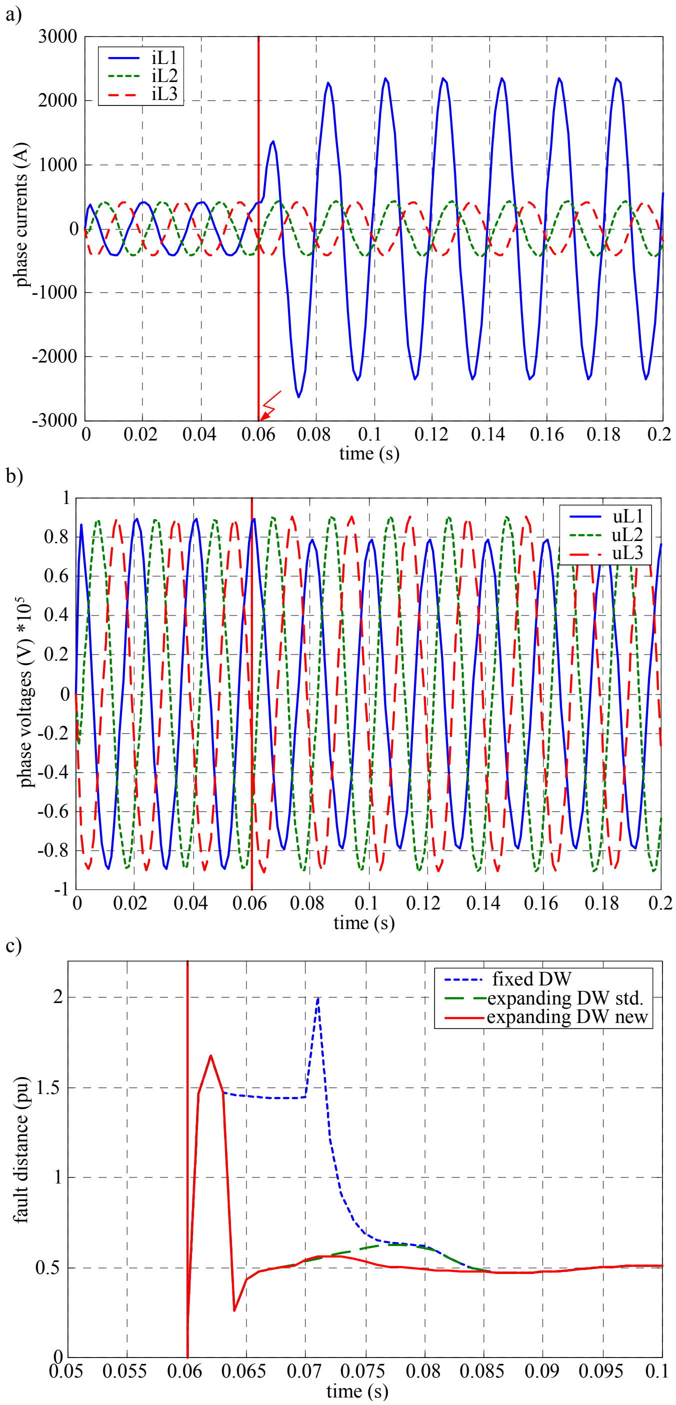

Fig. 5. Fault distance estimation for a single-phase-to-ground fault in the middle of line section A-T: a) phase currents, b) phase voltages, c) distance estimation results for various filter sets; measurements at station A.

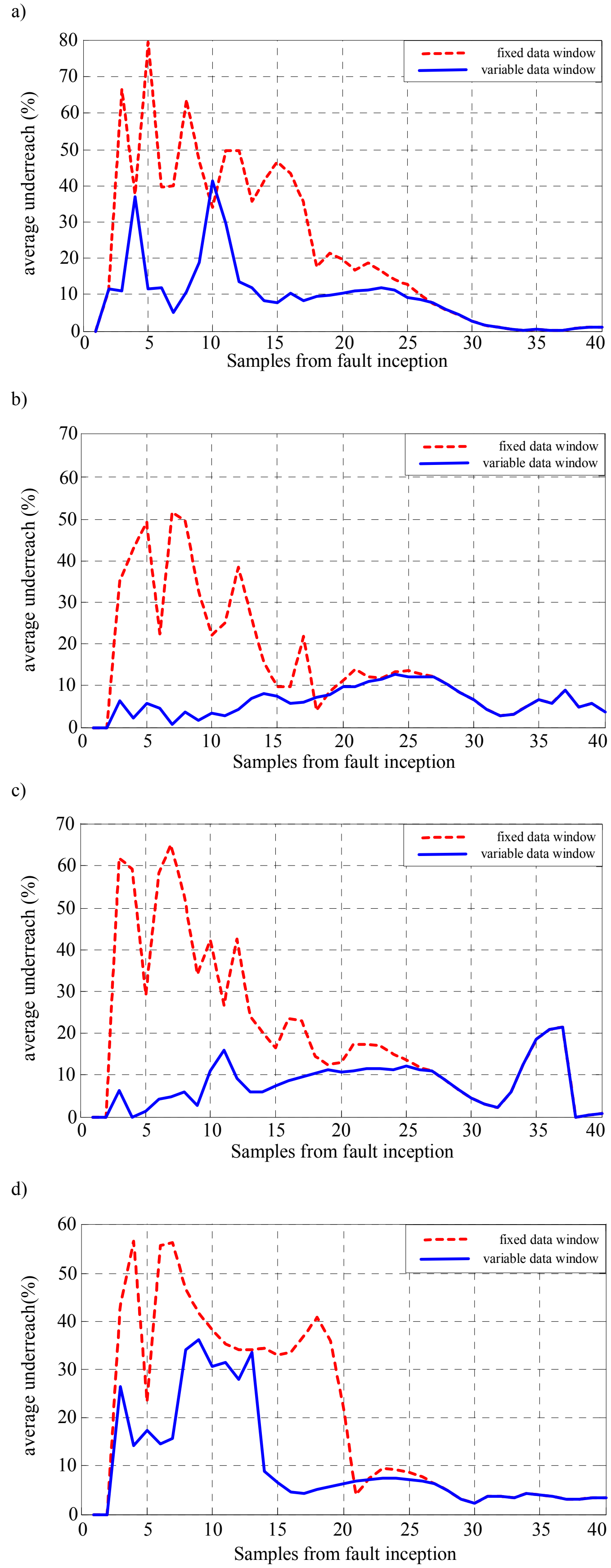

Fig. 6. Diagrams of average underreaching for particular fault types: a) L1-G, b) L1-L2, c) L1-L2-G, d) L1-L2-L3.

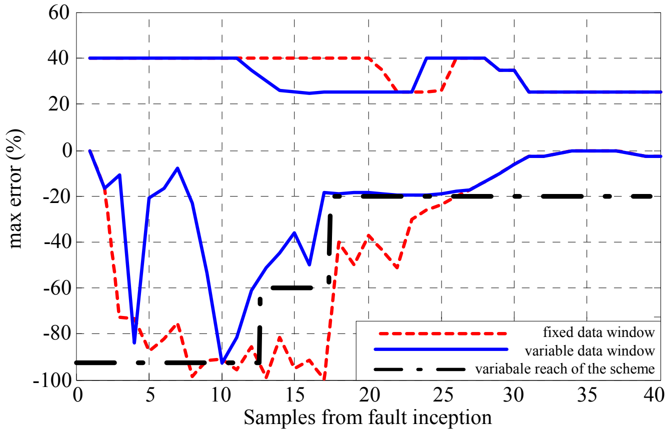

Fig. 7. Diagrams of maximum over- and underreaching for L1-G faults in 80-100% of adjacent sections.

In Fig. 7 the diagrams of maximal over- and underreaching, of fault distance estimation procedure are presented (here – for L1-G faults only). For the protection purpose the maximum negative errors (underreaching) are of the greatest importance. The bottom blue solid diagram in Fig. 7 can be utilized in adaptation of the protection zone Z1 reach. If the negative error exceeds 100% then the protection function for zone Z1 should be blocked.

Similar analyses can be also done for the other fault types. As a result of research, four sets of time-dependent thresholds have been worked up for definition of the variable first Zone reach. The functions in Table 1 have been proposed with the two preliminary assumptions taken as follows:

a) the reach values have to be less than the worst case values of underreach at every time instant,

b) the reach function has to be a non-decreasing one.

TABLE 1: PROPOSAL OF THE DEVELOPING REACH OF ZONE1 IN TIME DOMAIN.

L1-G		L2-L3		L2-L3-G		L1-L2-L3	
sampl.	thres.	sampl.	thres.	sampl.	thres.	sampl.	thres.
1-13 14-17 18-∞	0.10 0.40 0.80	1-32 33-∞	0.78 0.80	1-38 39-∞	0.60 0.80	1-15 16 17-∞	0.20 0.60 0.80

This adaptation method should result in much faster and yet reliable tripping as compared to the approach based on fixed data window filtering.

B. Performance of the distance algorithm with adaptable reach point

The performance of the proposed adaptive relaying algorithm has been assessed with the use of all fault cases simulated within 5% up to 80% of the length of adjacent line sections (T-B, T-C). For particular fault types appropriate first Zone reach characteristics were applied. In Fig. 8a it is well visible that the average trip time is a rising function of the fault location. The time is close to 10ms for faults in vicinity of *T* point and increases to almost 20ms for faults at the end of adjacent lines. Comparative studies performed for the algorithm employing fixed full-cycle window filters and suitably modified relay reach characteristics brought about the results showing that response of such a relay is some 7-10ms slower (Fig. 8b), which confirms advantages gained by applying new variable window filter based protection scheme.

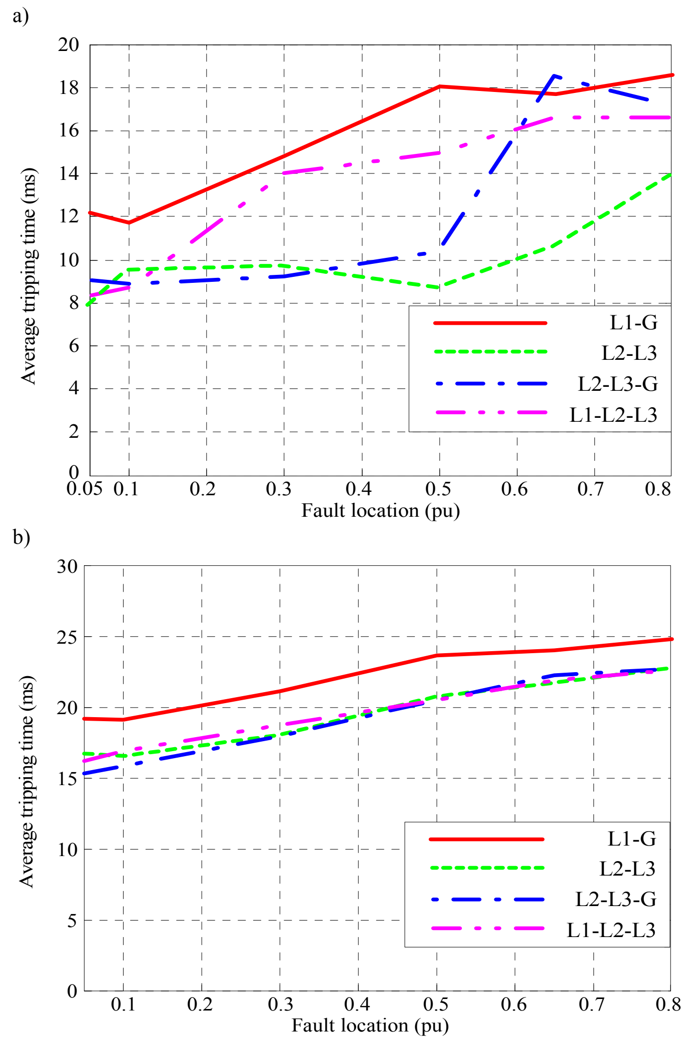

Fig. 8. Average trip time versus fault distance for the algorithm with: a) variable window filters, b) fixed window filters.

IV. CONCLUSIONS

The research carried out for an adoption of a conventional fault location algorithm with utilization of the new variable window filtering for the tee'd line protection allows drawing few conclusions related to its possible application in a real-time digital relay:

- the average trip time of the new variable window adaptive protection is less than one cycle (from 8 to 19ms, depending on the fault type);
- it has been shown that the use of orthogonal filters with variable data window allows shortening of tripping times and increasing of dynamic reach of the protection;
- application of adaptable thresholds makes the protection algorithm immune to transients resulting from both fault phenomena and measurements dynamics with employed variable data window filters;
- the algorithm is not a typical distance protection approach; it is sensitive to changes in system configuration, thus an

adequately frequent update of settings (source impedances and magnitudes of pre-fault currents at the opposite busbars) is essential for reliable operation of the method;

- the method is quite complex and its application in real-time digital relay will require the use of adequate capacity of the main processor; however, coarse analysis has proved that it is utterly feasible with present-day available processors.

V. Acknowledgments

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VI. References

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VII. Biographies

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Seung-Jae Lee (S'1978, M'1988) was born in Seoul, Korea in 1955. He received BS and MS degrees from Seoul National University, Seoul, Korea in 1979 and 1981, respectively and Ph.D. from University of Washington, Seattle, USA in 1988. Since 1988 he has been with the Department of electrical Engineering, Myongji University, Yongin, Korea as a Professor. He is also a director of Next Generation Power Technology Center. His main research areas are protective relaying, distribution automation and AI applications to power systems.