Wave Propagation Regime to Point to Faulted Feeder in Mixed Cable-and-Line Distribution Systems with Single-Line-to-Ground Fault

W.-Y. Huang, R. Kaczmarek

Abstract--In radial distribution network with no discontinuities in feeders' impedances the shape of traveling wave induced by a single line to ground (SLG) fault inception is modeled by multiple refractions and reflections from busbar, fault and loads. Only initial propagation zone presents a rigorous polarity disposition of residual currents, with sound residuals having the same polarity. We can determine the minimal sampling frequency necessary to get in that zone the current data indicating faulted feeder. The initial polarity length does not depend on the fault position, its resistance value or on the soil resistivity, and if scrutinized on all feeders it can point out from busbar to faulted feeder in systems with laterals.

The propagating waves can thus be involved in directional procedures in lines or in cables. Under certain conditions the faulted feeder detection can be assumed also in mixed networks, built up partly of cables and partly of lines.

Keywords: Traveling waves, fault detection, distribution systems

I. Introduction

Used in transmission lines, the traveling waves haven't as yet found confirmation in distribution systems, where feeders are short and impedance mismatches are frequent. First approaches have been tempted to fault distance calculation, but researches of characteristic frequencies have proved as yet inefficient [1]. The coordination by GPS of traveling wave's data has been reported efficient in this task [2], but involving GPS on distribution level may be onerous.

In our opinion, as far as the traveling waves in distribution systems are concerned [3], the detection of faulted feeder is more realistic challenge than fault distance calculation.

Necessity of extremely rapid fault detection has been reported, in less than 1ms [4], when equipment was to be protected against excessive currents. In this area the rapidly proliferating underground cables installations are of special concern because with characteristic impedance several times lesser comparing to overhead lines, they produce higher discharging currents. The latter are usually considered as useless and must be filtered in order to get into charging currents which are carriers of useful information [5].

We think that strong discharging currents, sometimes generating unfavorable conditions for protection relays in compensated systems, can be exploited as carriers of relevant information at a price of higher sampling frequency.

High frequency of acquisition, of 1MHz order [4], sensor's saturation with high dynamics of discharging currents and obligation of installing sensors on every feeder are main drawbacks here. We propose an all current approach with reasonable frequency requirements, being insensible to sensor saturation and to regime of grounding.

It is worthwhile to note that wave velocity in cables may be about half the velocity in overhead lines, somewhat relieving high frequency stress on acquisition. After fault inception we dispose of several tens of microseconds to get the data in wave propagation area what imposes the acquisition frequency of 100kHz.

Magnetic cores saturation, an important obstacle to acquisition accuracy of transient currents with large dynamics, is not relevant in our approach, where sensors need to send only a logical value, which is possible to acquire even after the device has entered the saturation.

As to number of sensors involved it should be noted that new ideas on directional all-current procedures appear in form of a distributed protection [6] with current sensors on each feeder. The fault would be located on amplitude detection all along the way from fault to busbar. The necessary selectivity however may be not assured on well compensated networks.

We think it is possible to assure such selectivity if the sensors record initial polarity during the propagation phase where we look for currents' polarities to identify the faulted feeder.

II. Detection of Faulted Feeder in Simple Radial Systems

The profiles of discharging currents becoming rapidly inextricable because of multiple reflections and refractions of traveling waves, and on the other hand being overshadowed by rapidly developing charging currents, we think it useful to isolate a very short initial interval of clear waveform profiles where the critical condition is frequency of acquisition rather than heavy analysis of frequencies. Hence the duration of this interval in several topological cases will be here our concern.

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The following has been modeled in EMTP with frequency dependent parameters.

A. Overhead system

We consider a simple overhead line network with three radial feeders a,b,c with an SLG fault occurring on feeder a. The analyzed data are residual current waves as recorded by sensors on the busbar side of each feeder.

During initial traveling waves' regime the current residuals arriving on busbar present rigorous disposition of polarities, as the sound feeders have the same polarity which is opposed to the one on faulted feeder. This disposition can be perturbed when a current wave returns from the shortest sound feeder after reflection on its load. The time it takes to travel to and fro along the shortest feeder determines the initial polarity zone δ_{ip} and gives the minimal frequency of acquisition necessary to get data pointing to faulted feeder (1)

$$f_{\min} = \frac{1}{\delta_{ip}} = \frac{v}{2l_{\min}} \qquad (1)$$

with v – the zero sequence mode velocity and l_{minn} – the length of the shortest feeder.

With the shortest feeder's length of 19.4km the smallest frequency required is 7kHz (Fig. 1) and for robustness reasons – rather several times greater.

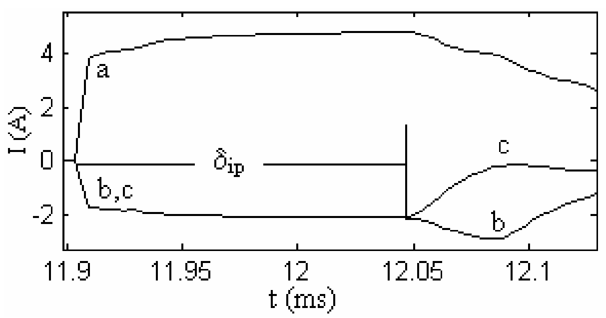

Fig. 1. Three feeder system a+b+c = 36.8+24.2+19.4km , residual currents recorded on busbar side with a resistive SLG fault of R_f= 1kΩ on feeder a at 1/10 of feeder length from busbar. At t=12.05ms the wave returning from the shortest feeder c may change the initial polarity on this feeder. The initial polarity period δ_{ip}=0.144ms

B. Underground cable system

After the fault inception cables are siege of waves traveling both in cores and sheaths, a core–to–sheath fault giving almost the same waveforms as a core–to–ground one. Fig. 2 presents an after-fault regime in a system of three feeder a,b,c with fault on the phase 3 of the feeder a, all sheaths being grounded on both ends.

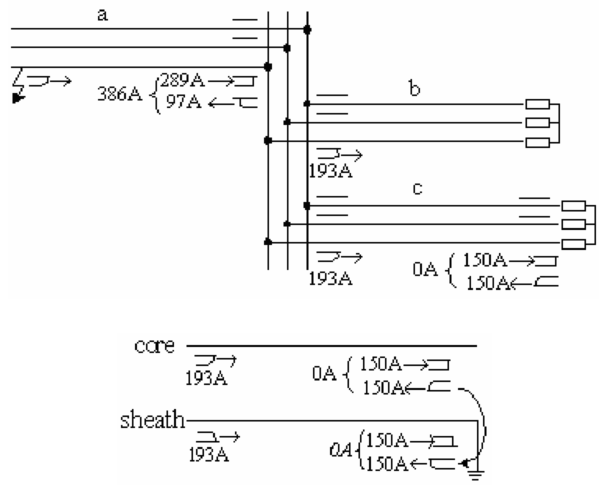

Fig. 2 Current waves disposition along cable in a three feeder system a+b+c = 18.4+12.1+9.7km, fault on feeder a. Upper: only cores are shown, bottom: core and sheath wave disposition on a sound feeder.

In the cable's core the current wave of -289A, accompanied in its sheath by magnetically induced synchronous wave of opposite polarity, arrives at busbar without exciting other phases because of mutual cancelling of external core and sheath fluxes (Fig. 2 upper part). There it superposes with its own reflection: -289A(1+1/3)=-386A. At busbar refraction the 386A wave is equally distributed between faulted phases on feeders b and c: -386A/2=-193A.

The residual currents are the sum on three cores currents. They are dominated by the faulted phase waves. Fig. 3 shows the simulated currents with paramount initial polarity zone, which for the shortest cable feeder of 9.7km lasts 0.123ms, giving a theoretical value for minimal frequency of acquisition of 8kHz.

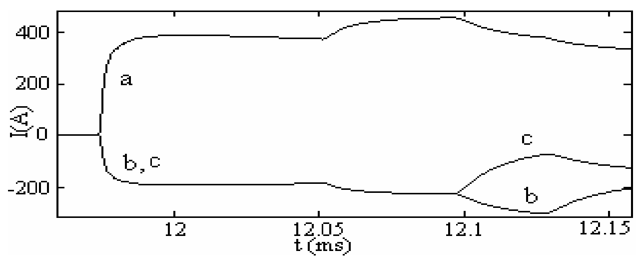

Fig. 3 After-fault residual current waves in a three feeder cable system 18.4+12.1+9.7km, fault of R_f=1Ω resulting in important amplitudes. δip=0.123ms

C. Mixed cable and line system

One of application of directional function based on analysis of the initial polarity zone may be with fault occurring on an overhead line in mixed systems, with cables on busbar side and overhead lines leading to loads. We present an analysis of a three feeder (a,b,c) system with 1:2 ratio of cable length to line length and an SLG fault on phase 3 of the feeder a. With the fault occurring on cable (Fig. 4) the high frequency amplitudes are several times higher comparing to the case of faulted line (Fig. 5) and may affect more seriously equipment isolation.

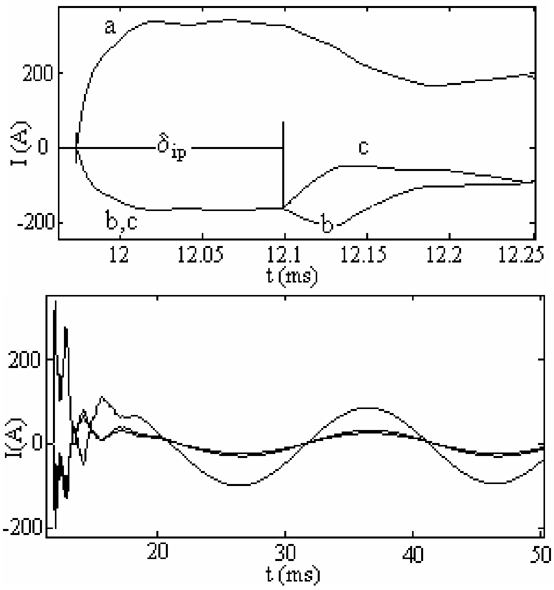

Fig.4 Residual currents with an SLG fault of R_f=1Ω in mixed feeder system (55.2+36.3+29.1km), with cable to line length ratio ½, the fault occurring on cable at 9/10 of the cable length. Upper – zoom on the traveling wane zone. δip=0.123ms, the reflexion wave returning from load arriving theoretically on busbar at t=12.24ms

When the fault occurs on overhead line near loads, the travelling wave from fault position to busbar refracts when meeting impedance discontinuity at the line-and-cable joint. In this case, the amplitude of arriving wave on busbar is smaller than the one induced by a fault occurring on cable.

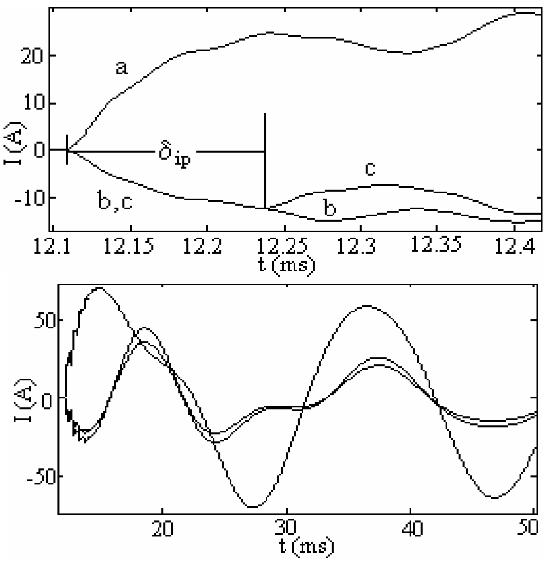

Fig.5 *idem*, the fault occurring on line at 9/10 of the line length. Upper – zoom on the traveling wane zone. δip=0.123ms, the reflexion wave returning from load arriving theoretically on busbar at t=12.376ms

Weather the fault occurs on cable in vicinity of the cable and line joint (Fig. 4) or on line near loads (Fig. 5) the initial polarity zone is the same δ_{ip}=0.123ms, its duration corresponding to time the wave takes to go to and fro between busbar and cable-and-line joint on the shortest feeder "c".

III. Detection of Faulted Feeder in Systems with Laterals

We consider a five feeders "a-e" network with a ramification on feeder "c" (Fig. 6) and cable sheaths grounded on both sides. Current sensors should be present at the beginning of each feeder, including laterals.

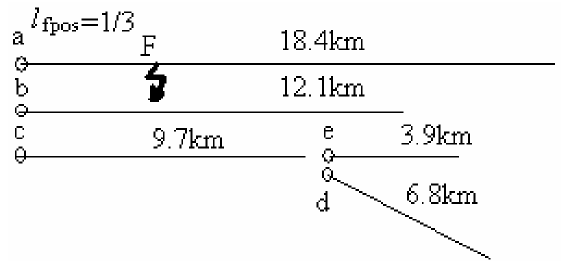

Fig. 6. Five feeders(A - E) network with one ramification and an SLG fault on feeder "d".

A. *Cable feeders*

With fault on feeder "a" the current waves along feeders (Fig 7) develop partly as in radial network.

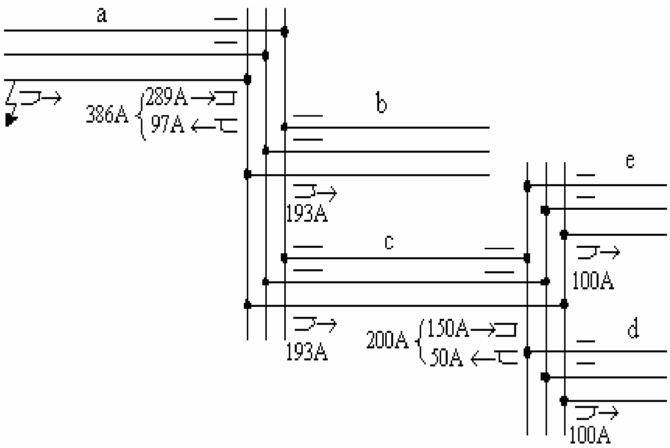

Fig. 7 Current waves disposition along cable in a five feeder system with ramifications, and SLG fault on the feeder "a" at 1/3 from busbar. Only cores are shown

The unique polarity of current waveforms at busbar points to the faulted feeder "a" (Fig. 8)

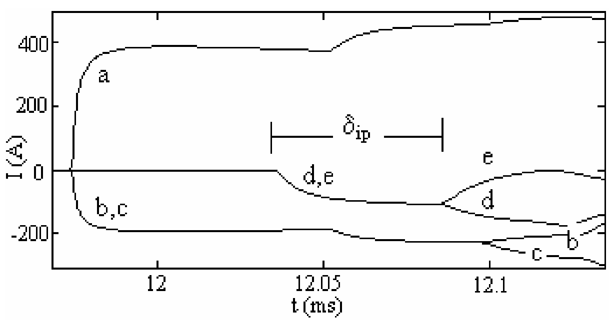

Fig. 8 The fault on feeder A pointed by current waves' polarity at busbar. δip=0.05ms

In general, the faulted feeder can be traced starting with identification on busbar of a unique sign, that we call “witness” sign, which is different from others. If the fault occurs on one of ramification, e.g. on “d”, then we follow all indications of the same polarity as the “witness” sign. The fault is at the end of the chain (“c” and “”d” on the Fig. 9). In case presented on the Figure 8 the polarity of “e”, which conforms locally to that of “a” (the witness sign), cannot point to fault because the intermediary feeder “c” is out of the supposed faulted chain.

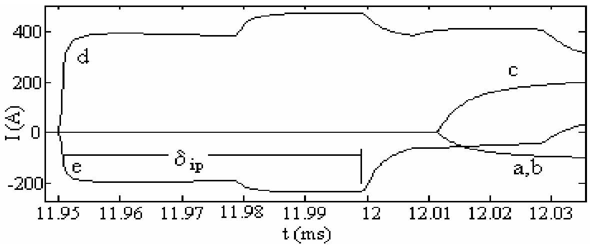

Fig. 9 The fault on feeder d, δip=0.05ms, same as in the of the Fig. 8.

B. *Mixed feeders*

The laterals “e” and “d” of the Fig. 6 are now prolonged with overhead lines of respectively, 11.7 and 20.4km. We analyze two cases: first, with fault occurring on cable segment of the feeder “d” (Fig. 10) at one third from busbar, and then with fault occurring on overhead segment of “d” (Fig. 11) at one tenth from loads. The waveform disposition showing the faulted feeder is fundamentally the same in both cases, with the same length of the initial polarity zone δ_{ip}=0.05ms. Consequently, at least 20kHz frequency of current acquisition is required, and realistically rather 100kHz.

We note (Figs 9 and 10) similitude of waveform disposition for cable system and the same cable system with feeders prolonged with lines. The latter don’t influence significantly the data for faulted feeder detection.

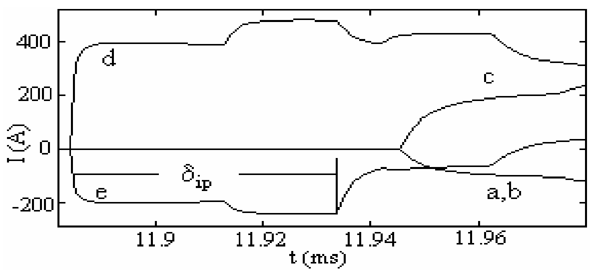

Fig. 10 The fault on cable part of the feeder “d”, δip=0.05ms.

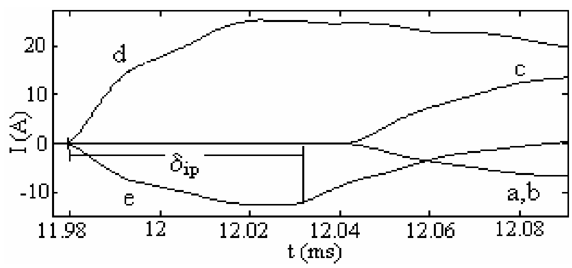

Fig. 11 The fault on overhead part of the feeder d, δip=0.05ms.

IV. Conclusions

The rapid identification of faulted feeder using automatic analysis of residual currents recorded in traveling wave zone can be assured at price of high acquisition frequency. We evaluate it on 100kHz in systems where the shortest cable feeder has length of several km. Impedance mismatch of mixed systems with laterals not an obstacle to the faulted feeder detection if sensors can be installed on every feeder.

V. References

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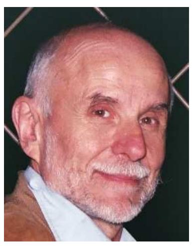
VI. Biographies

Wan-Ying HUANG has graduated from Tsing Hua University in Taiwan with Master Degree in 2002 and in 2006 has got her PHD in the Ecole Supérieur d’Electricité SUPELEC and University Paris XI in France. She is now on a post doctoral research program in SUPELEC, working on protections in distribution systems and optimal design of electric machines.



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