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Improvement of Overcurrent Protection Reliability Using Phasor Study

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Abstract:

Capability of the power system protection scheme to introduce a reliable and secure relay response has become a critical matter. Digital relays use special algorithms to filter unwanted components of the input signal and extract the fundamental component. Meanwhile, proper techniques must be used to prevent mal-trip of such relays, due to transient and harmonic currents in the network. This paper, presents using the real and imaginary part of current phasor in order to discriminate between fault and non-fault events. Some typical transient currents due to transformer energizing, capacitor switching and induction motor starting are simulated in Power Factory software and results of using the method are discussed and illustrated.

1) Introduction

After electromechanical and static relays, the third generations of protective relays are digital relays, which perfectly could accomplish the basic concepts of protective scheme like:

- Maintain dynamic stability
- Prevent or minimize equipment damage
- Minimize the equipment outage time
- Minimize the system outage area
- Minimize system voltage disturbances
- Allow the continuous flow of power within the emergency ratings of equipment on the system

While four criteria for protection should be considered:

- fault clearing time
- selectivity
- sensitivity
- reliability

Reliability is a measure of the protective relays system's certainty to trip when required (dependability) and not to trip falsely (security). Most microprocessor relays use digital filter to extract only the fundamental and either attenuate or eliminate harmonics.

The principle of relay protection is based on stable status values of power system parameters. When the parameter is at transient status the protection principle doesn't necessarily guarantee correct operation of the relay. The transient currents which are quite common in the network can be related to either fault or un-fault events. It is therefore important to evaluate the possible response of protective relays when the input parameters contain transients [1]. Some of the typical non-fault events that generate transient currents can be transformer energizing, capacitor switching and motor starting. Since such transient currents are generated during normal operation of power system components. They shouldn't lead to mal-trip of protective relays, which are installed for tripping the protected component only when there are faults.

On the other hand the growth of non-linear leads like pulse rectifier, variable speed drivers and uninterruptible power supplies that present harmonics, DC and other components might shadow the proper performance of relays [2]. When a transient current is detected by an overcurrent relay, the only information that the relay can get is the signal waveform of the current. To classify the transient currents in term of relay mal-trip impact, the analysis should start form relay operation and detection principles. Then using some methods in the relay algorithm, digital relay could distinguish between fault or non-fault situation more accurately. One of these methods could be on the basis of real and imaginary components of current phasor that is explained in the paper.

2) Principle of Digital Protective Relays

The main advantages of digital relays over conventional relays are their reliability, functional flexibility, self-checking and somewhat self-adaptability.

They are able to implement more complex functions, be more accurate and be immune from physical environment effects. Although they are relatively costly, the benefits in enhancing system security and reliability by adopting these relays can make their application worthwhile.

A digital relay consists of the following main parts:

- Processor
- Analog input system
- Digital output system
- Independent power supply

Fig. (1) shows the block diagram of digital relay [3].

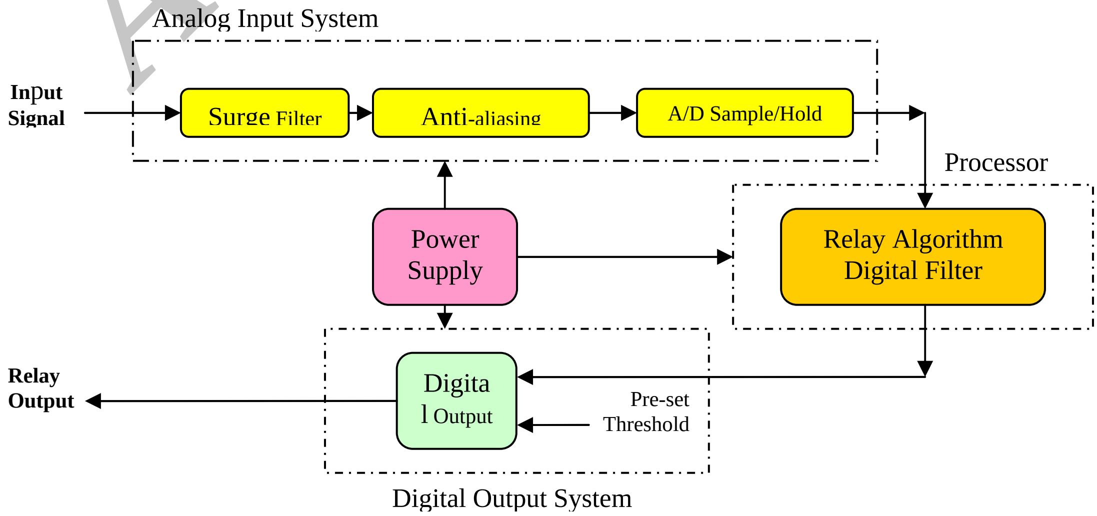

Fig. (1) The block diagram of digital relay

In the analog input system, a surge filter is used to suppress the large inrush in the input signals, for the safety of the digital Relay. An anti-aliasing filter is used to avoid possible errors in reconstructing the input signal, which is carried out after the A/D Sample/Hold section. Any signal sampled at a frequency of N*50 Hz (or N*60 Hz in North America) can exhibit aliasing when reconstructed, if the signal contains harmonic components of order N±1, 2N±1, …, xN±1. An anti-aliasing filter has to cut off all signal components above the Nyquist rate of N/2, i.e. the cut-off frequency for anti-aliasing filter should be set not higher than (N/2)*50 Hz. In practice however, such a filter cannot remove all out of band frequencies, so the cut-off frequency for the anti-aliasing filter is typically set at about (N/3)*50 Hz. The A/D sample and hold circuit is adopted to convert the input signal from analog to digital. To scan the whole signal, a data window of limited length is applied to acquire information on part of the signal. In Fig.(2), it is illustrated that the input signal is frozen by the data window to achieve simultaneous sampling at each moment, when the oldest sample point is discarded and the newest one is embedded. These samples are held until the next sampling moment. The sampling window length, sampling number in the window as well as the shape of the sampling window is dependent on the relay algorithm stored in the processor.

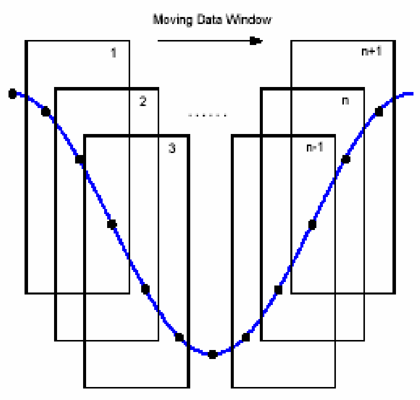

Fig. (2) Data window for sampling

The philosophy of digital filters is to remove the unwanted components as much as possible so as to extract the fundamental component from the input signals. Several filters are available for this purpose. The most common ones are Fourier, Walsh, and Kalman filters.

3)Effect of transient currents on relay response

It should be considered that in the power system, when a fault occurs there are harmonics, inter-harmonics and DC components in the current wave form. On the other hand, there are some non-fault events in the system that seems to distort the waveform in the similar way [4].

3-1) Transformer Energizing

When a transformer is energized, there is a transient inrush of current that is required to establish the magnetic field of the transformer. For the worst-case energizing the flux in the core may reach a maximum of twice the normal flux. For flux values much greater than normal, the core will be driven deep into saturation, causing very high-magnitude energizing inrush current to flow. The magnitude of this current is dependent on such factors as supply voltage magnitude at the time of energizing, source impedance, and residual flux in the core, transformer size, and design. This initial energizing inrush current could reach values as high as 25 times full-load current and will decay with time until a normal exciting current value is reached. The decay of the inrush current may vary from as short as 20 cycles to as long as minutes for highly inductive circuits [5]. The inrush current contains all orders of harmonics, both odd and even orders. Although the digital relay filter is used to extract the fundamental component of the current, the magnitude of the signal may lead to mal-trip of the relay. Another concern about transformer energizing is transient propagation. This normally happens during transformer energizing, which causes considerable amount of even harmonics and DC component in the voltage. These disturbances may propagate through transformers to therest of the system, and be magnified due to resonance effect. Because of this, the load currents at other busbars can be severely distorted, which might have detrimental impact on the locally installed current relays. Fig. (3) shows this propagation trend. The current through the load feeder at busbar B can be affected by the disturbance propagated from transformer energizing at busbar A.

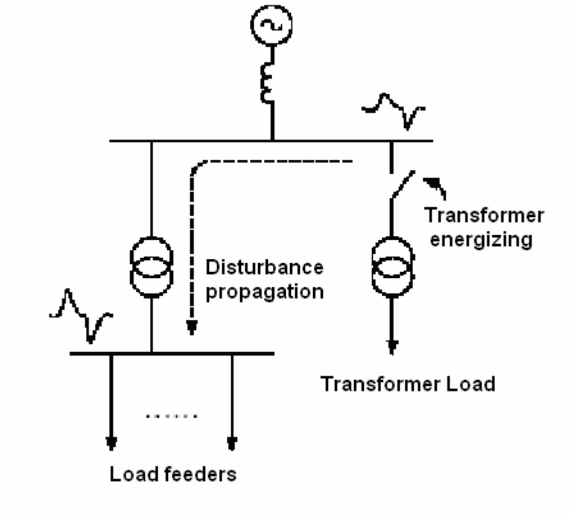

Fig.(3) Disturbance propagation due to transformer energizing

3-2) Capacitor Switching

Capacitor switching is common mostly in MV and LV distribution systems. The dynamic effect of capacitor energizing is a severe oscillation in voltage and current, with frequencies from 300 to about 1000 Hz. This transient can propagate through the system, especially when other capacitors are present [6]. The principle of isolated capacitor energizing is shown in Fig. (4). Isolated capacitor energizing means that no other capacitor is connected nearby before the capacitor bank is switched. In some cases, capacitor de-energizing leads to an increase in current magnitude. This potentially endangers the operation of overcurrent protection as well.

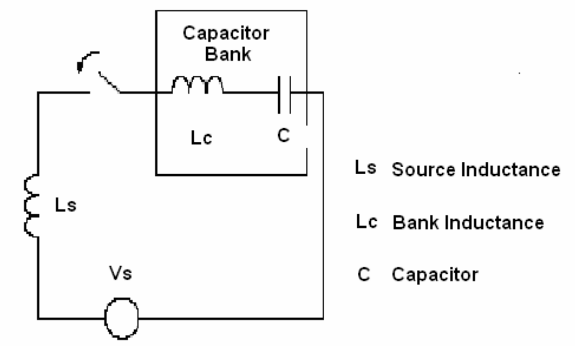

Fig. (4) Isolated capacitor energizing

The maximum peak value of the inrush current due to isolated capacitor energizing can be calculated using the following equation:

$$I_{peak} = \sqrt{2}V_s\sqrt{\frac{C}{L_s + L_c}} \qquad (1)$$

Where, V_s is the RMS value of the pre-switching voltage.

3-3) Motor Starting

Motor starting that happens in MV and LV systems is another subject to be considered. The starting of a large induction motor leads to an inrush current, which is typically 5 to 6 times the normal operating current. This large current may be present for several seconds. Generally starting time of a motor is less then 5 or 6 seconds. But it can be as high as 20 to 30 seconds for motors having loads with high inertia. Thus puts a severe strain on overcurrent protection. Also under-voltage protection is potentially affected [7].

4) Using Current Phasor Components for a Secure Protection

Microprocessor relays execute mathematical procedures and produce analytic characteristics that can be described accurately by equations. We therefore have the opportunity to calculate relay response to any specified waveform. The key to the behavior of microprocessor relays is the output of the digital filter. This is obtained by sampling sine-wave currents and/or voltages at discrete time intervals.

In this paper for example, to obtain the current phasor components a first sample taken at an arbitrary time on a current sine wave is the instantaneous dc value representing $I\cos(\omega_0 t+\theta)$, where θ is an arbitrary phase angle. A second sample taken 90° later is $I\sin(\omega_0 t+\theta)$. Consequently, just taking two samples 90° apart extracts the real and imaginary components of a phasor.

The term “filtering” is used because the magnitude of the components change when the sampling interval remains fixed, and the input frequency is varied. The filter output then varies in magnitude and phase as a function of the input frequency. Consequently, more than two samples per cycle are used, and filter coefficients are selected to obtain a favorable frequency response.

Here, a 16 sample/cycle full cycle cosine filter is particularly suited for protective relaying [8]. While extracting the fundamental, the filter rejects all harmonics including the decaying exponential and will be used in the subsequent cases. The filter in equation form appears as follows:

The filter coefficients:

$$CFC_n = \cos\left[\frac{2\pi}{16} n\right] \qquad (2)$$

The Cosine filter:

$$IX_{smpl+spc} = \frac{2}{N+1}\sum_{n=0}^{N} I_{smpl+spc-n} CFC_n \qquad (3)$$

The phasor magnitude:

$$|Io|_{smpl+spc} = \sqrt{(IX_{smpl+spc})^2 + (IX_{smpl+spc-\frac{spc}{4}})^2} \qquad (4)$$

The phasor output:

$$Io_{smpl+spc} = IX_{smpl+spc} + j.IX_{smpl+spc-\frac{spc}{4}} \qquad (5)$$

where:

N =15
n =0, 1, 2… N
smpl = sequence of samples 0, 1, 2, 3…
spc =number samples per cycle (16)
$I_{smpl+spc-n}$ =Current sample
$IX_{smpl+spc}$=Filter output
Io =filter derived current phasor

In equation (3), any value of smpl indicates that 16 samples of the current have been stored. The index n ranges from 0 to 15 to apply the coefficients and sum the samples to produce the output. With 16 samples/cycles, 4 samples represent 90 electrical degrees. Therefore, in equation (5), the present output together with the output recorded four samples before constitute the real and imaginary components of the phasor.

To explain the method practically, a part of a network is simulated in the Power Factory software. Several non-fault switching events are applied to this system along with some short circuit events at different times. The simulation results show how the phasor components of transient currents could help the overcurrent relay to find the distinction between fault and non-fault situations.

4-1) Transformer Energizing

In order to study transformer energizing a sub-transmission system is simulated. So that, the inrush current may be considerable. As shown in Fig.(5) an external slack network feeds the system. General information of the network are as follows:

External grid: V=1∠0, S"= 10000MVA
Transformer A: 100 MVA, 230/63 KV
Transformer B: 50 MVA, 230/63 KV

Some events have been defined that produce transient currents in this system. The transformer is switched off and on again at the time 0.5 and 1 seconds respectively. A short circuit event occurs after the transient time has been past. The short circuit is a three phase symmetrical one at bus-3 at the time 8 second and the short circuit impedance is 5 ohms.

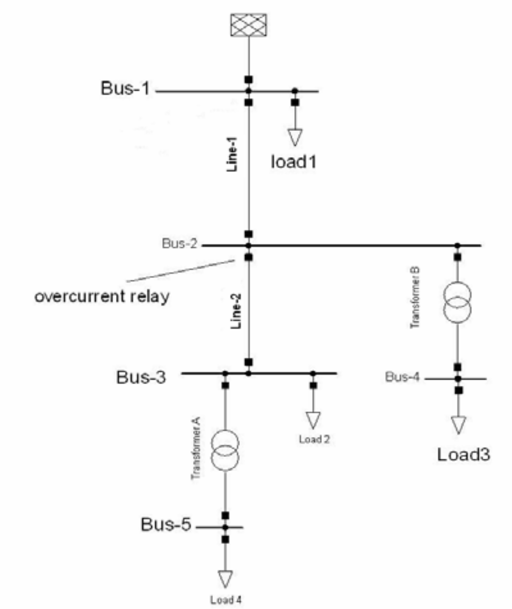

Fig. (5) Power system topology for Transformer Energizing Study

The overcurrent relay is installed at the beginning of line-2 that trips 0.1 second after the occurrence of the fault. The real and imaginary components of line-2 current phasor are calculated by the relay algorithm as explained before. Regarding Fig.(6), which shows the waveform of these two current components, the transformer energizing shows its transient effect mainly on imaginary part. While the short circuit event doesn't have that much effect on this part but mostly on real part of current, so gives us a good factor to separate these two events.

Changing the fault type or the short circuit occurrence time, the results are mostly alike. For example the simulation results with a single phase short circuit event, is illustrated in Fig. (7).

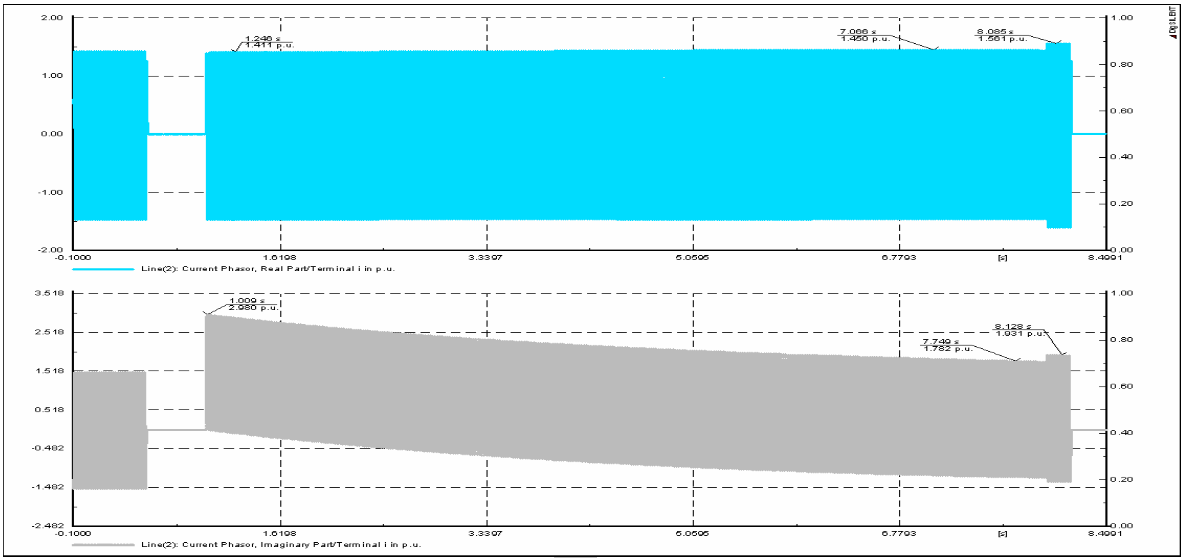

Fig. (6) Real and Imaginary part of Relay Current due to transformer energizing (three-phase short circuit)

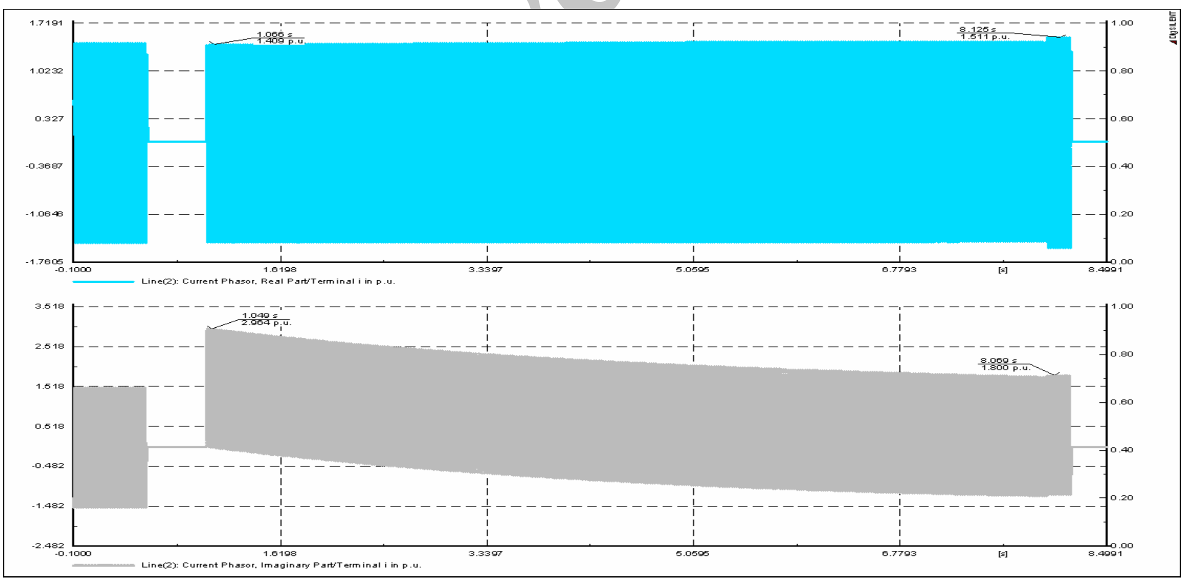

Fig. (7) Real and Imaginary part of Relay Current due to transformer energizing (single-phase short circuit)

4-2) Capacitor Switching

For capacitor switching, an industrial system is simulated in Power Factory. The voltage levels of this network are 11 and 0.4 KV. Some general information about this network are as follows:

External grid: V=1∠0, S"= 1000 MVA
Transformer A: 2 MVA, 11/0.4 KV
Induction motor: 1 MW
Capacitor bank: 2 MVAR

The single line diagram of this system is shown in Fig.(8). The capacitor is switched off and on again at the time 0.5 and 1 seconds respectively to produce a switching transient. A three phase short circuit happens at time the 1.5 second on bus-2. And it is cleared by the relay at 1.7 second. Waveforms of the current components are shown in Fig. (9) The change of the fault to a single phase fault makes a little change in current signal but doesn’t disturb the rule.

This is gained from Fig.(10) that the increasing ratio of imaginary component to the real component is because of a no-fault event. In the case of a fault, the real part increases in a higher rate than the imaginary part or at least they increase in the same rate.

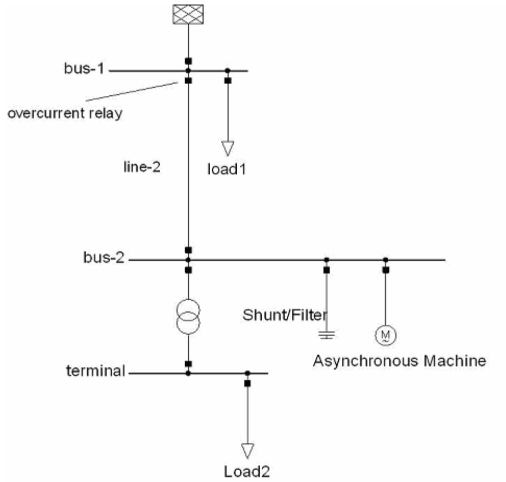

Fig.(8) Power system topology for Capacitor Switching and Motor Starting study

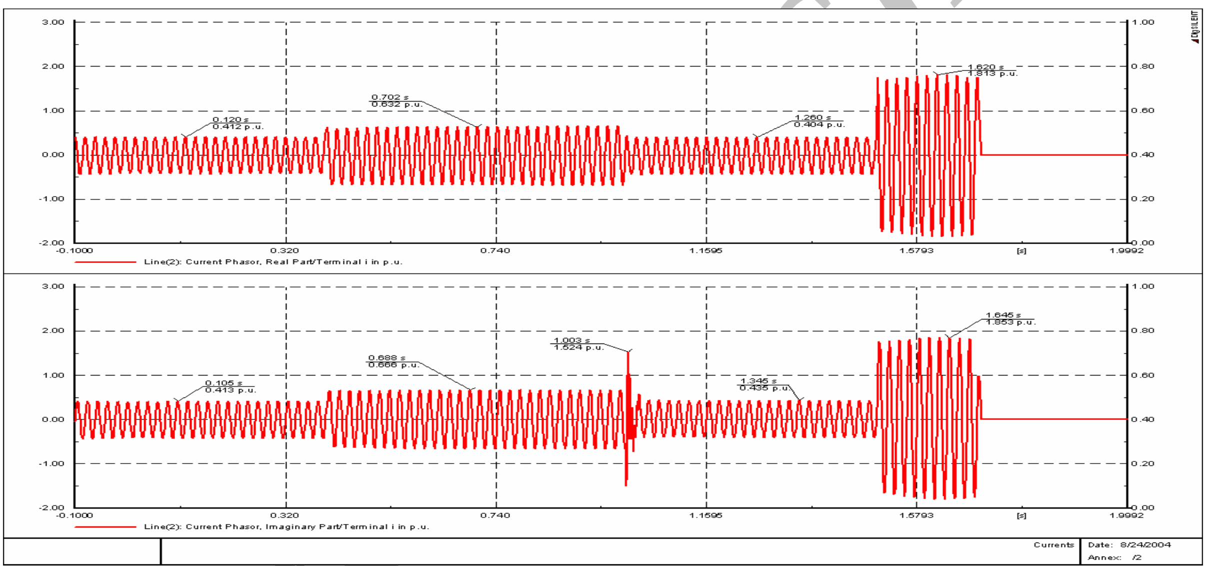

Fig. (9) Real and Imaginary part of Relay Current due to capacitor switching (three-phase short circuit)

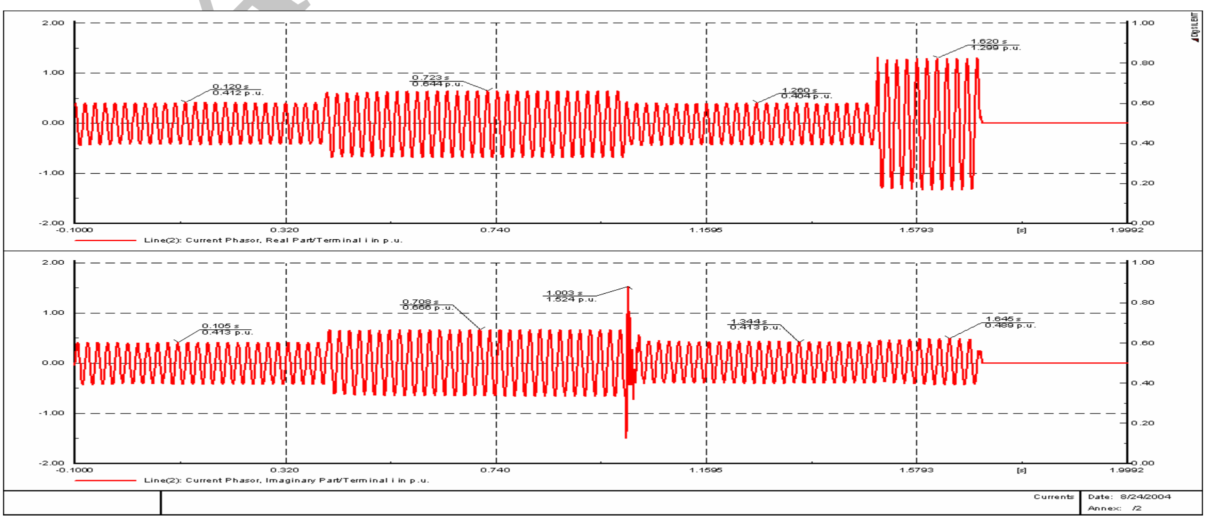

Fig. (10) Real and Imaginary part of Relay Current due to capacitor switching (single-phase short circuit)

4-3) Induction Motor Starting

The same network as for capacitor switching is simulated for deriving motor starting transients. With the same system information, the induction motor is disconnected from the network at 0.5s and it's switched on at time1 second. In order to compare with a faulted event, a three phase short circuit occurs at the time 1.5 seconds on bus-2 And it is cleared by the relay 0.2 second later. As shown in Fig.(11), although the fundamental current magnitudes for both fault and no-fault events are the same but again, the most increase of the current in motor starting is in imaginary part of the phasor. In Fig.(12) the current waveforms are depicted for a single line to ground fault. It should be considered that just for motor starting, because the inrush current is dependent on the time of switching, different starting times should be studied before setting of the relays.

In general, the phasor components introduce a good factor of distinction in power system overcurrents.

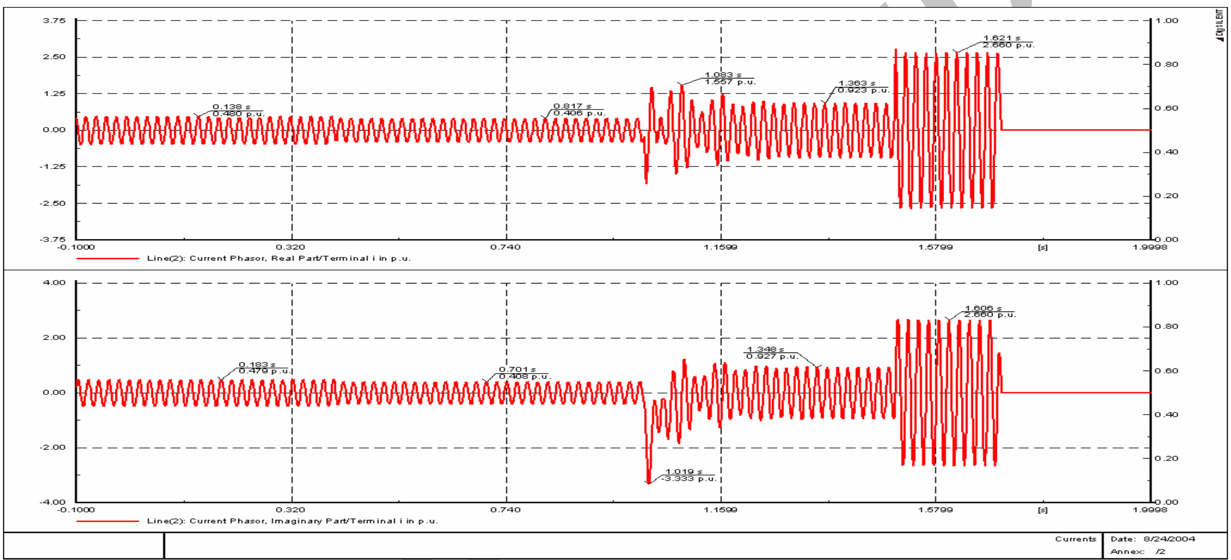

Fig. (11) Real and Imaginary part of Relay Current due to motor starting (three-phase short circuit)

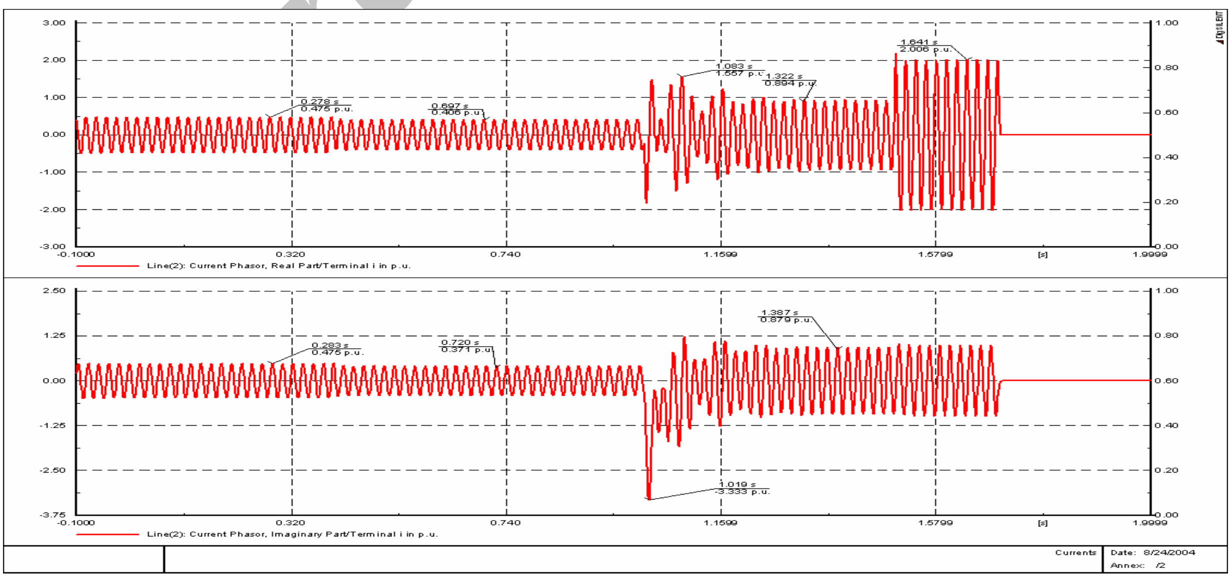

Fig. (12) Real and Imaginary part of Relay Current due to motor starting (single-phase short circuit)

5) Conclusion

In this paper, a simple method of improving overcurrent relays reliability was introduced. The simulation results indicate that most of non-fault overcurrents affect the imaginary component of current phasor more than the real one. As these two components are available from digital relay's basic algorithm, it doesn't take extra time for the processor to calculate them. Three common non-fault events where simulated in example networks and the results were acceptable. This paper had a general view over on-hand parameters that could help relay selectivity. Even though, other studies are necessary to cover more circumstances.

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