

## A Novel Method for Frequency Estimation Considering Instrument Transient Effect

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### ABSTRACT

Large disturbances in power systems cause deviation in the frequency from the nominal value. Since the frequency is an important factor in the electrical network parameter measurements, it can cause malfunction of the protection system. In addition, Because of decaying DC and oscillatory components that introduced by CCVT in response of voltage variation during the fault occurrence, cause changes in the value of received voltage of primary side of CCVT. An improved least square method for estimating frequency is presented in this paper. In order to reduce the effect of this transient component, phasor estimation method has been improved by using the least square technique and utilizing knowledge of CCVT design. The capability of the proposed method was verified by several case studies generating signals in PSCAD/EMTDC. The results show the accuracy, speed and capability of the proposed method.

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## 1. INTRODUCTION

The most important devices used for power system security, are protective relays. in the presence of fault, these devices must identify the faulty section or component correctly and quickly and isolate it so that other sections of the network have a minimum impact. This simple and basic requirement is hard to achieve in presence of transient components due to fault, which is present in voltage and current signals received by the protective device. The coupling capacitor voltage transformer (CCVT) is one of the main devices whose transient response impacts on performance of a distance relay. Although the voltage output of CCVT at steady-state condition is accurate, its behavior during transient causes inaccuracy in phasor calculation. Moreover Frequency is a significant operating parameter of a power system. Precise monitoring of the frequency of a power system is important to optimal operation, especially a real-time precise estimation of the main frequency is necessary for electrical parameter measurements. This is because numerous numerical methods for electrical parameter measurements are sensitive to frequency fluctuations.

Several methods for estimating frequency have been mentioned in the technical literature [1-18]. Zero-crossing methods are the most widely used methods for estimating frequency [1, 2]. However, their performance is Impressive to switching-type transients. The Kalman filter has also been utilized for frequency estimation in power system [3, 4], but it is highly affected by the initial conditions and its performance is not robust due to deviations in the internal parameters of the model. A three-phase, phase-locked loop (PLL) prepares quick and robust frequency estimation for balanced three-phase networks and has been widely used for estimating frequency [5-7]. Nevertheless, its performance is prone to error in unbalanced conditions. different approaches, consist of least square methods [10, 11], DFTs [14-16],

Newton-based algorithms [12], and the maximum likelihood approach [17], adaptive neural networks (ANN) [8, 9], complex Prony analysis [13, 18] have also been utilized for frequency estimation of power system signals.

A new dynamic frequency estimation method is suggested in this paper. This method which is based on least square technique uses the CCVT transient information in the voltage waveform which is displayed during transient condition. Some case studies such as signal test and also significant cases for fault in transmission line are presented. Signal is generated by PSCAD/EMTDC software. With CCVT information and proposed algorithm, the results show that speed of convergence and accuracy has been improved in the frequency.

## 2. BACKGROUND

### 2.1. Effective Factors on the Transient Response of a CCVT

The most significant factors that impact the CCVT transients response are the power factor and magnitude of secondary burden, the incidence angle of fault, voltage change magnitude and Ferro resonance Suppression Circuit (FSC) of CCVT [21], [22].

#### 2.1.1. Burden

Most CCVT models give proper performance during the transient state for burdens lower than the nominal burden. Whenever, the power factor decreases, CCVT transient response becomes worse. Parallel RL circuits' burdens for the same volt-ampere and power factor give the worse transient response than Series RL [21]. The inductive burdens found in electromechanical relays cause more CCVT transients state than the resistive burdens found in digital and numerical relays [23].

#### 2.1.2. Fault Incidence Angle

Incidence angle of the fault causes changes in CCVT transient behavior. [23]. For a voltage peak transient, the resulting similar is an under damped system that will cause a transient voltage that oscillates at a frequency larger than the power frequency. A voltage zero transients cause an overshoot voltage that damps to zero in a few cycles. In this case, the subsidence voltage will result in a reduced voltage magnitude and shifted phase angle [24]. Faults at zero crossing of the primary voltage cause significant transient errors that result in the operation of covered protective relays [25].

#### 2.1.3. FSC Type

There are two types of FSCs, 'passive' type, which do not store energy and 'active' type, which stores energy [20], [21]. Active ferroresonance suppression circuits (AFSC) have parallel connection of iron core inductors and capacitors, which is adjusted to the power frequency. These circuits consistently connected on CCVT secondary side [23], [26]. The AFSC behaves like a band-pass filter and causes additional time delay in the CCVT secondary output. The energy storage components in the AFSC participate to the intensity of the CCVT transients [23]. Passive ferroresonance-suppression circuits (PFSC) consist of a consistently connected loading resistor and a saturable inductor. The saturable inductor is designed to saturate at about 150% of rated voltage to hold up a sustained ferroresonance condition [23]. These FSCs do not change transient response of CCVT unless an overvoltage occurs [26].

#### 2.1.4. Magnitude of Voltage Change

The fault voltage magnitude level is the significant factor that affects the intensity of CCVT transients. In the lower voltage level, the transient response of Secondary voltage wave of CCVT is more heterogeneous in during the fault. The voltage change magnitude depends to source to line impedance ratio (SIR) value, fault location, and fault resistance [23]. A higher SIR causes into a larger magnitude voltage change at the relay location on the onset of a fault [22], which can result in higher overreach difficulties.

## 2.2. Equivalent Circuit of a CCVT

A general coupling capacitor voltage transformer (CCVT) includes a capacitive voltage divider, tuning reactor, step-down transformer and Ferro resonance suppression circuit. During fault conditions, because of the voltage drops, there is no threat of over passing the knee-point of the magnetizing characteristic of the step-down transformer, so a CCVT can be expressed by the equivalent linear circuit as illustrated in Figure 1. In this paper the CCVT model shown in Figure 1. The linear circuit of Figure 1 can be further simplified as shown in Figure 2. The parameters in the circuit of Figure 2 are:

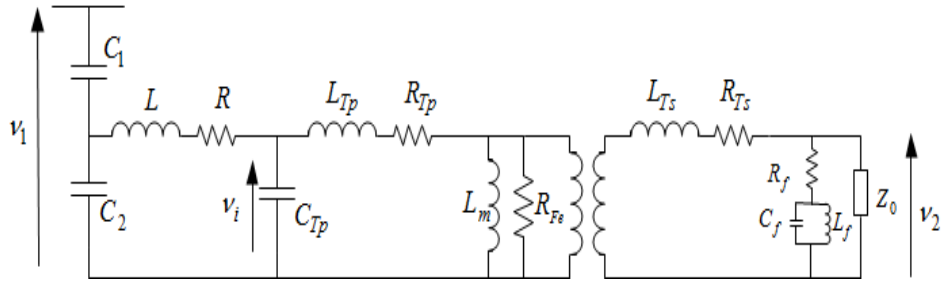


Figure 1. Equivalent circuit diagram of a CCVT

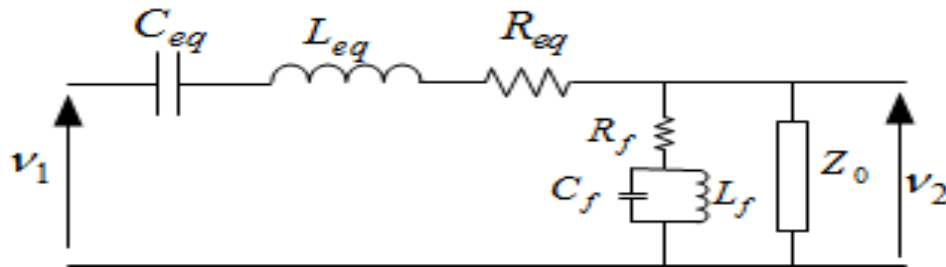


Figure 2. Simplified model of a CCVT from Figure 1

$C_{eq}$  is sum of the stack capacitances,  $L_{eq}$  and  $R_{eq}$  are equivalent inductance and resistance respectively, of the tuning reactor and the Step down transformer,  $Z_0$  is burden impedance,  $f$  is subscript for parameters of the anti-resonance circuit.

As mentioned in [19], the transfer function of a CCVT derived for the model of Figure 2 is:

$$G(s) = \frac{K_{CCVT} (s - z_1)(s - z_1^*)(s - z_2)(s - z_3)}{(s - p_1)(s - p_1^*)(s - p_2)(s - p_2^*)(s - p_3)} \quad (1)$$

Where  $z_i$ s is zeros of CCVT transfer function and  $p_i$ s are poles of CCVT transfer function and:

$$p_1 = -\alpha_1 + j\omega_1 \quad (2)$$

$$p_2 = -\alpha_2 + j\omega_2 \quad (3)$$

$$p_3 = -\alpha_3 \quad (4)$$

Where  $p_1$  is low frequency pole,  $p_2$  is high frequency pole and  $p_3$  is dc pole.

### 3. PROPOSED METHOD

In order to investigate the behavior of CCVT, the CCVT input signal has been considered during fault occurrence has been considered as following:

$$v(t) = Be^{-\frac{t}{\tau}} + A_1 \sin(\omega t + \varphi_1) + \sum_{i=2}^N A_i \sin(i\omega_0 t + \varphi_i) \quad (5)$$

Where  $B$  is the amplitude and  $\tau$  is the time constant of decaying dc signal,  $A_i$ s are harmonic components including signal fundamental component,  $\omega_0$  is fundamental angular frequency which  $\omega_0 = 2\pi f_0$

and  $f_0$  is the main frequency of the system. The exponential DC term of signal is created when fault occurs in the network and the other sinusoidal expressions are second and higher order harmonic of signal of voltage.

As has been mentioned in [19], the CCVT amplitude frequency response is such that DC component and high-frequency components eliminates and also strengthens or weakens frequency of around the power frequency. The fifth-order transfer function can be used to represent CCVT behavior [19]. According to this model, the output signal from CCVT is generally to be considered as follows:

$$\begin{aligned}\hat{v}(t) = & V_r \cos(\omega t) + V_i \sin(\omega t) \\ & + V_{r1} e^{-\alpha_1 t} \cos(\omega_1 t) + V_{i1} e^{-\alpha_1 t} \sin(\omega_1 t) \\ & + V_{r2} e^{-\alpha_2 t} \cos(\omega_2 t) + V_{i2} e^{-\alpha_2 t} \sin(\omega_2 t) + V_{dc} e^{-\alpha_{dc} t}\end{aligned}\quad (6)$$

Where  $V_r$  and  $V_i$  are real and imaginary parts of voltage phasor of fundamental components,  $\alpha_1$  and  $\omega_1$  and  $\alpha_2$  and  $\omega_2$  are real and imaginary parts and  $\alpha_{dc}$  is dc component pole of the transfer function of CCVT. Utilizing Taylor series,  $\sin(\omega t)$ ,  $\cos(\omega t)$  can be expanded as below :

$$\sin(\omega t) \approx \sin(\omega_0 t) + t \Delta \omega \cos(\omega_0 t) - \frac{t^2}{2} \Delta \omega^2 \sin(\omega_0 t) \quad (7)$$

$$\cos(\omega t) \approx \cos(\omega_0 t) - t \Delta \omega \sin(\omega_0 t) - \frac{t^2}{2} \Delta \omega^2 \cos(\omega_0 t) \quad (8)$$

By substituting Taylor series expansion in (6), the output signal of the CCVT can be represented as follow:

$$\begin{aligned}\hat{v}(t) = & V_r \cos(\omega t) + V_i \sin(\omega t) + V_r' t \cos(\omega t) \\ & + V_i' t \sin(\omega t) + V_r'' t^2 \cos(\omega t) + V_i'' t^2 \sin(\omega t) \\ & + V_{r1} e^{-\alpha_1 t} \cos(\omega_1 t) + V_{i1} e^{-\alpha_1 t} \sin(\omega_1 t) \\ & + V_{r2} e^{-\alpha_2 t} \cos(\omega_2 t) + V_{i2} e^{-\alpha_2 t} \sin(\omega_2 t) + V_{dc} e^{-\alpha_{dc} t}\end{aligned}\quad (9)$$

### 3.1. Calculation of Phasor

Damping oscillatory components and dc decaying component of the voltage signal which is created during the fault occurrence, cause the unsuccessful estimation with basic least square method. in order to overcome this problem, it must be considered that the components of transient response CCVT has been extracted from the equivalent circuit section 2.1, phasor estimation can be improved by the least squares method. According to the equation (9) can be written:

$$\hat{V} [m \times 1] = D [m \times 11] \times E [11 \times 1] \quad (10)$$

where:

$$\hat{V} = [\hat{v}(t_1) \quad \hat{v}(t_2) \quad \hat{v}(t_3) \quad \hat{v}(t_4) \quad \dots \quad \hat{v}(t_m)]^T \quad (11)$$

$$[D]_{m \times 11} = [[d_1]_{m \times 3} \quad [d_2]_{m \times 3} \quad [d_3]_{m \times 1} \quad [d_4]_{m \times 2} \quad [d_5]_{m \times 2}] \quad (12)$$

$$E = [V_r \quad V_r' \quad V_r'' \quad V_i \quad V_i' \quad V_i'' \quad V_{dc} \quad V_{r1} \quad V_{i1} \quad V_{r2} \quad V_{i2}]^T \quad (13)$$

where in (12)

$$d_1 = \begin{bmatrix} \cos(\omega t_1) & t_1 \cos(\omega t_1) & t_1^2 \cos(\omega t_1) \\ \cos(\omega t_2) & t_2 \cos(\omega t_2) & t_2^2 \cos(\omega t_2) \\ \cos(\omega t_3) & t_3 \cos(\omega t_3) & t_3^2 \cos(\omega t_3) \\ \vdots & \vdots & \vdots \\ \cos(\omega t_m) & t_m \cos(\omega t_m) & t_m^2 \cos(\omega t_m) \end{bmatrix} \quad (14)$$

$$d_2 = \begin{bmatrix} \sin(\omega t_1) & t_1 \sin(\omega t_1) & t_1^2 \sin(\omega t_1) \\ \sin(\omega t_2) & t_2 \sin(\omega t_2) & t_2^2 \sin(\omega t_2) \\ \sin(\omega t_3) & t_3 \sin(\omega t_3) & t_3^2 \sin(\omega t_3) \\ \vdots & \vdots & \vdots \\ \sin(\omega t_m) & t_m \sin(\omega t_m) & t_m^2 \sin(\omega t_m) \end{bmatrix} \quad (15)$$

$$d_3 = \begin{bmatrix} e^{-\alpha_k t_1} \\ e^{-\alpha_k t_2} \\ e^{-\alpha_k t_3} \\ \vdots \\ e^{-\alpha_k t_m} \end{bmatrix} \quad (16)$$

$$d_4 = \begin{bmatrix} e^{-\alpha_k t_1} \cos(\omega_1 t_1) & e^{-\alpha_k t_1} \sin(\omega_1 t_1) \\ e^{-\alpha_k t_2} \cos(\omega_1 t_2) & e^{-\alpha_k t_2} \sin(\omega_1 t_2) \\ e^{-\alpha_k t_3} \cos(\omega_1 t_3) & e^{-\alpha_k t_3} \sin(\omega_1 t_3) \\ \vdots & \vdots \\ e^{-\alpha_k t_m} \cos(\omega_1 t_m) & e^{-\alpha_k t_m} \sin(\omega_1 t_m) \end{bmatrix} \quad (17)$$

$$d_5 = \begin{bmatrix} e^{-\alpha_k t_1} \cos(\omega_2 t_1) & e^{-\alpha_k t_1} \sin(\omega_2 t_1) \\ e^{-\alpha_k t_2} \cos(\omega_2 t_2) & e^{-\alpha_k t_2} \sin(\omega_2 t_2) \\ e^{-\alpha_k t_3} \cos(\omega_2 t_3) & e^{-\alpha_k t_3} \sin(\omega_2 t_3) \\ \vdots & \vdots \\ e^{-\alpha_k t_m} \cos(\omega_2 t_m) & e^{-\alpha_k t_m} \sin(\omega_2 t_m) \end{bmatrix} \quad (18)$$

In the equation (10)  $\hat{V}$  and  $E$  are value of known and unknown factors respectively and  $D$  is the matrix of known values. The equation (19) is obtained by using the method of least squares (LS):

$$E = (D^T D)^{-1} D^T X \quad (19)$$

By calculating this matrix, real and imaginary values of the signals will be obtained.

$$\bar{V} = V_r + jV_i \quad (20)$$

### 3.2. Frequency Estimation

In practice, three phase fault doesn't occur constantly. Actually the continuity of single phase faults which are much more common causes phase-phase and three phase faults and also voltage unbalances. Solving this problem, positive sequence of the voltage signals can be used [27]. In other words, voltage positive sequence is always available under balanced and unbalanced conditions.

Referring to above reasonable assumptions, the positive sequence of voltage signal can be considered into two orthogonal components as follows:

$$V_r(t) = V_m \cos(\omega t + \theta) \quad (21)$$

$$V_i(t) = V_m \sin(\omega t + \theta) \quad (22)$$

By differentiation of equations (21) and (22) and the placement in each other, the following equation is obtained:

$$f = \frac{V_{re}(t)V'_{im}(t) - V_{im}(t)V'_{re}(t)}{2\pi(V_{re}^2(t) + V_{im}^2(t))} \quad (23)$$

Also for created calculation error by approximate differentiation, it can be written:

$$f_{error} = \frac{2\pi^2 f_0^3 \Delta T^2}{3} \quad (24)$$

As a result, the frequency can be calculated as follows:

$$f_{estimated} = f + f_{error} \quad (25)$$

### 3.3. Algorithm Implementation and Computation Process

The proposed algorithm is described in previous section. Computing process of the algorithm is shown in Figure (3):

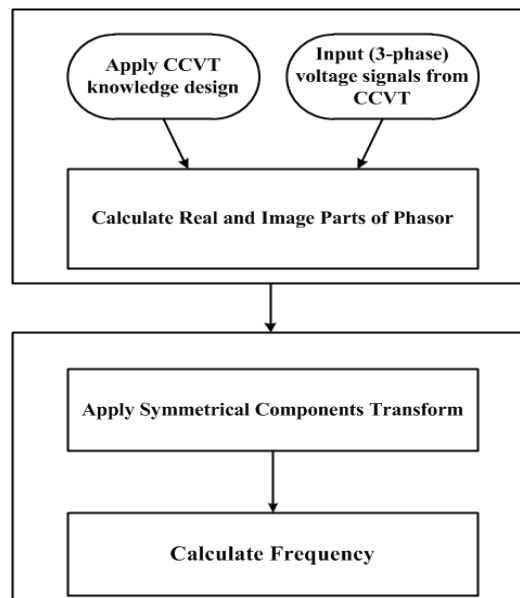


Figure 3. Stages of phasor and frequency estimation

#### 4. CASE STUDY

Dynamic conditions are analyzed using the Electromagnetic Transients Program (PSCAD/EMTDC) to simulate the simple system. As mentioned in section 3; the frequency response of the CCVT, contains attenuated high order harmonic components. Nevertheless, to prevent the presence of high order harmonic components, the second order butterworth lowpass filter with 360 Hz cutoff frequency has been used. Also the 5 KHz sampling frequency has been selected. In order to evaluate the performance of the proposed method (PM), the results of the PM have been compared with Nonlinear Least Squares (NLS) [9], Recursive Discrete Fourier Transform (RDFT) [14] and Adaptive Method (AM) [11]. As shown in figure (4), several dynamic conditions have been selected: double phase-to-ground faults, three phase-to-ground and single phase-to-ground faults in different locations.

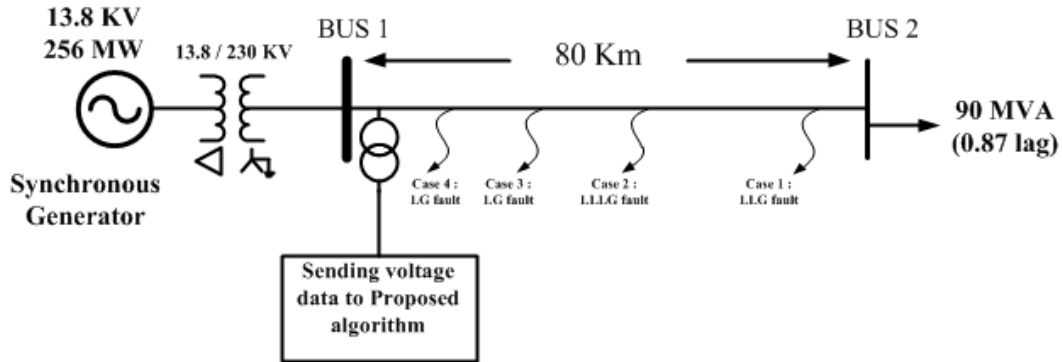


Figure 4. Four kinds of dynamic conditions: double phase-to-ground faults, three phase-to-ground and single phase-to-ground faults in different locations

##### 4.1. Case1

Figure (5) shows the time response of the phase A voltage signal for LLG fault condition with a fault incidence angle of  $0^\circ$  degrees. A magnitude of voltage change of 24% ( $= 100\% - 76\%$ ) of the pre-fault amplitude was observed at this location of the power system selected.

Figure 6 illustrates the frequency of the voltage phasor has been estimated using the (PM). As can be seen in figure (6), proposed approach causes estimated frequency converge to original value after 1 cycle. The results show that AM, RDFT and NLS methods have more sensitivity to Transient component produced by CCVT in voltage signal. That's the reason that frequency converge to original value after 3 to 5 cycles when CCVT impact is not considered.

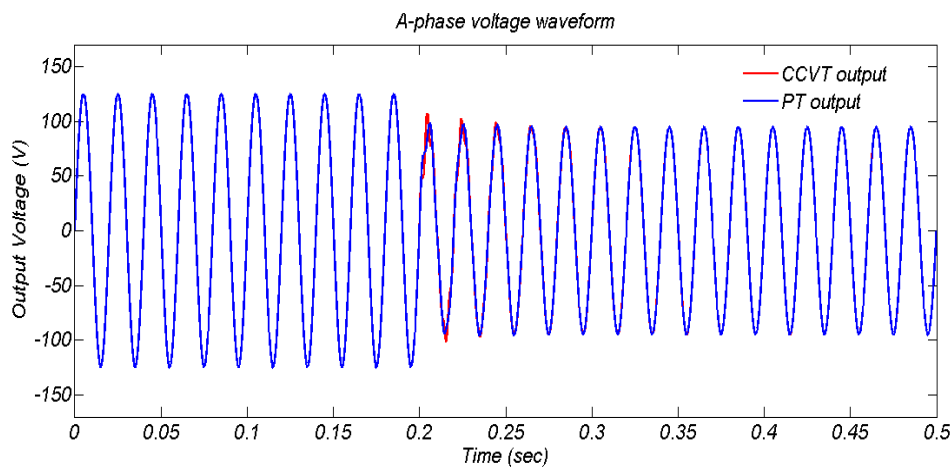


Figure 5. A-phase voltage waveform of the low resistance LLG fault stages of phasor and frequency estimation

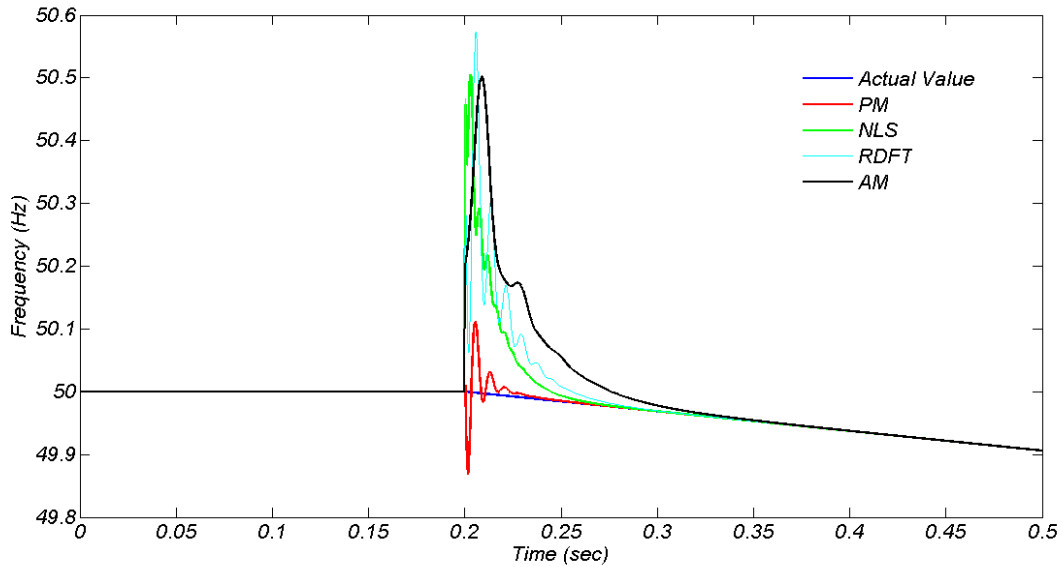


Figure 6. CCVT impact on Frequency during first cycles after fault occurrence

#### 4.2. Case2

Figure (7) shows the time response of the phase A voltage signal for LLLG fault condition with a fault incidence angle of  $90^\circ$  degrees. A magnitude of voltage change of 56% (= 100% – 44%) of the pre-fault amplitude was observed at this location of the power system selected.

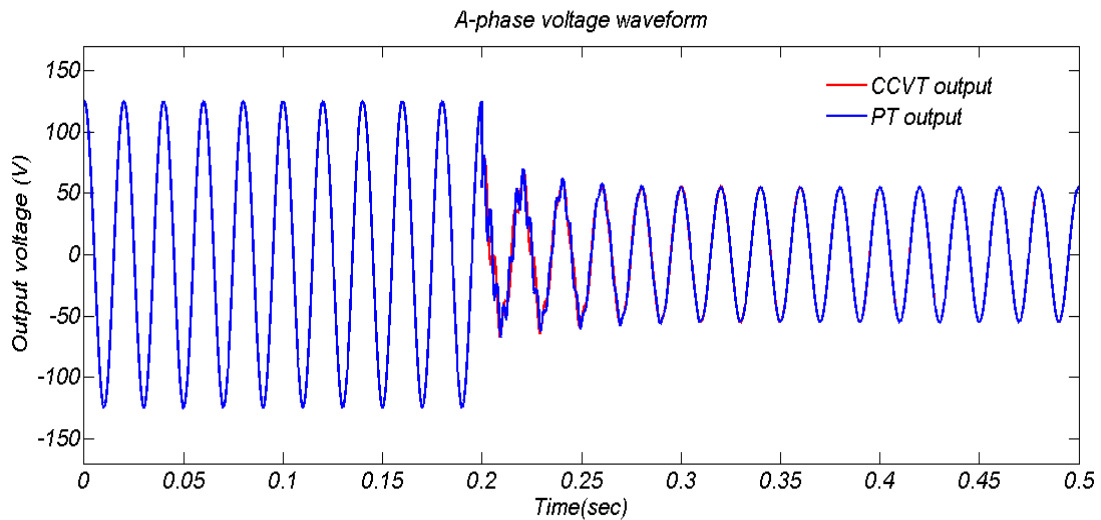


Figure 7. A-phase voltage waveform of the low resistance LLLG fault

Figure (8) illustrates the frequency of the voltage phasor which has been estimated using the proposed method. As can be seen in figure 8, although the stresses produced in voltage signal have been increased, the proposed approach estimated frequency converges to original value after 1 cycle. As shown in figure 8, without consideration of CCVT impact, it takes 3 to 6 cycles for frequency to converge to original value.



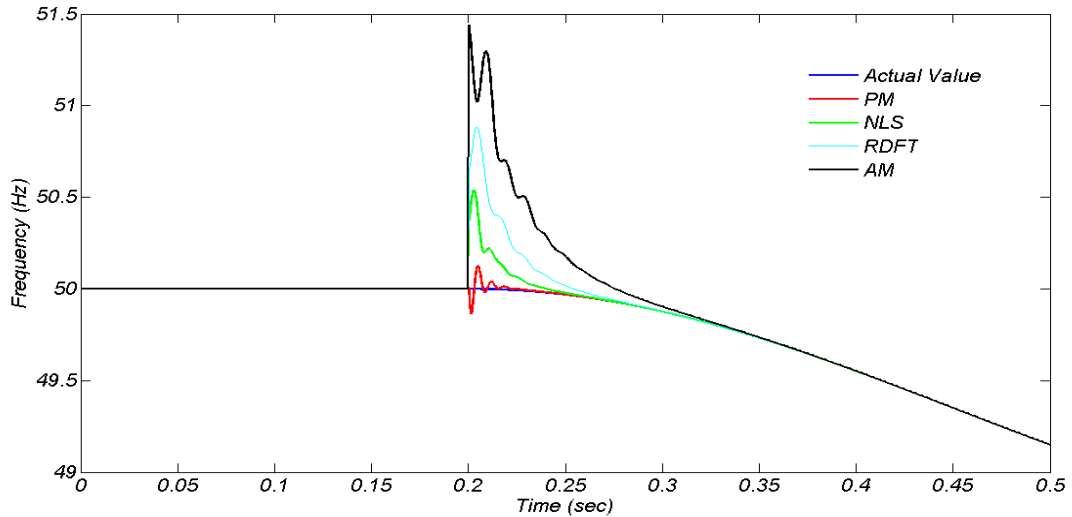


Figure 8. Impact on Frequency during first cycles after fault occurrence

#### 4.3. Case3

Figure (9) shows the time response of the phase A voltage signal for LG fault condition with a fault incidence angle of  $30^\circ$  degrees. A magnitude of voltage change of 64% (= 100% – 36%) of the pre-fault amplitude was observed at this location of the power system selected.

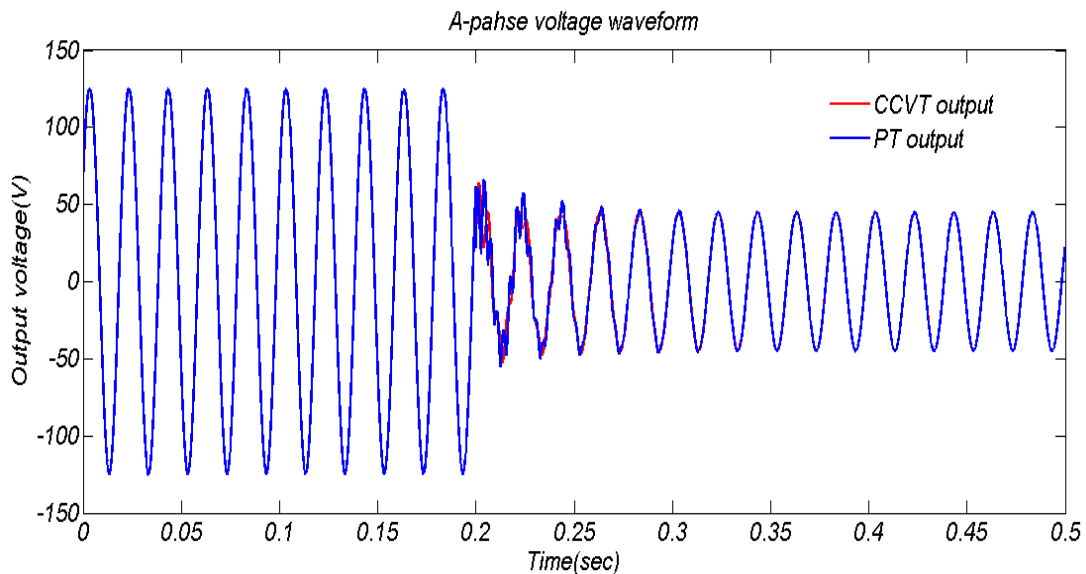


Figure 9. A-phase voltage waveform of the low resistance LG fault

Figure (10) illustrates the frequency of the voltage phasor estimated using the proposed method. As it is shown figure 10, when fault location approaches to the generator bus, stresses in voltage waveform increase. Nevertheless estimated frequency of the proposed method converges to original value after 1 cycle with minimum error. As the results of the proposed method show, consideration of CCVT impact results high precision in transient period in comparison with the other methods.

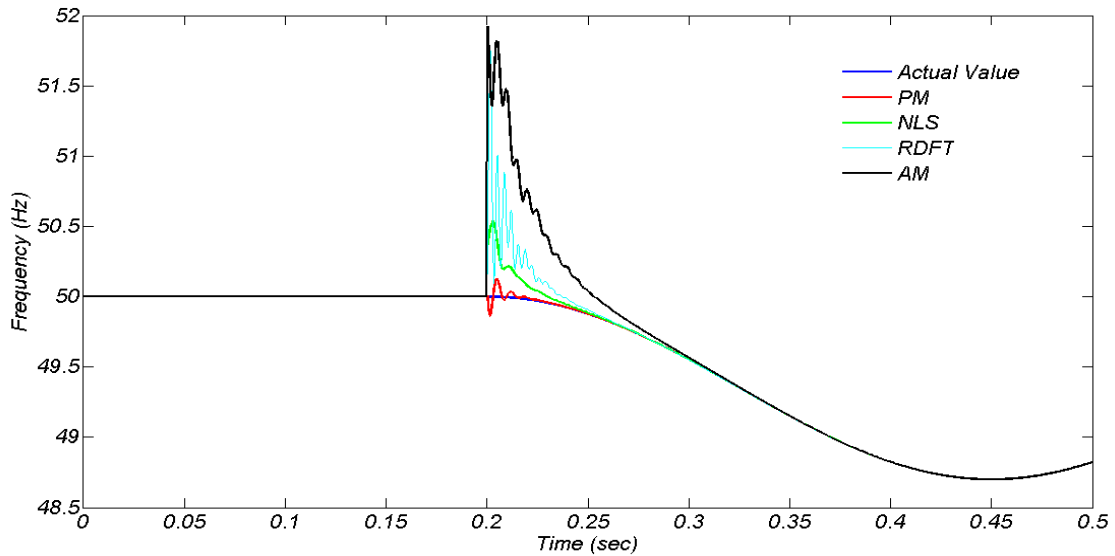


Figure 10. Impact on Frequency during first cycles after fault occurrence

#### 4.4. Case4

Figure (11) illustrates the time response of the phase A voltage signal for LG fault condition with a fault incidence angle of  $90^\circ$  degrees. A magnitude of voltage change of 90% ( $= 100\% - 10\%$ ) of the pre-fault amplitude was perceived at this location of the power system selected. As can be seen in figure 11, tension in voltage waveform have been enhanced.

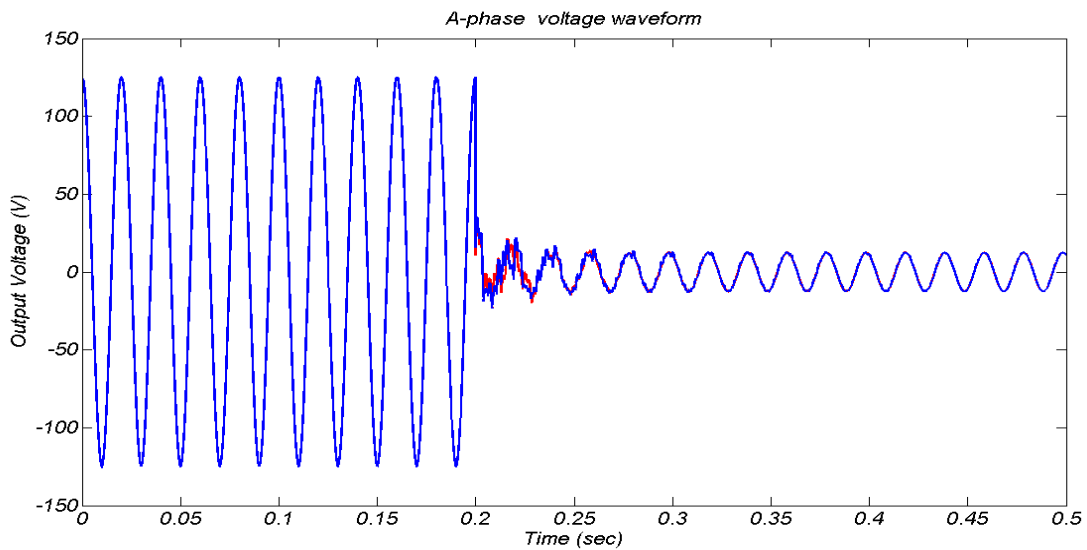


Figure 11. A-phase voltage waveform of the low resistance LG fault

Figure (12) illustrates the frequency of the voltage phasor estimated using proposed approach. As shown in figure 12, proposed approach causes estimated frequency converge to original value after 1 cycle. Despite of tension increment, the proposed approach has more significant accuracy in comparison with the other methods.

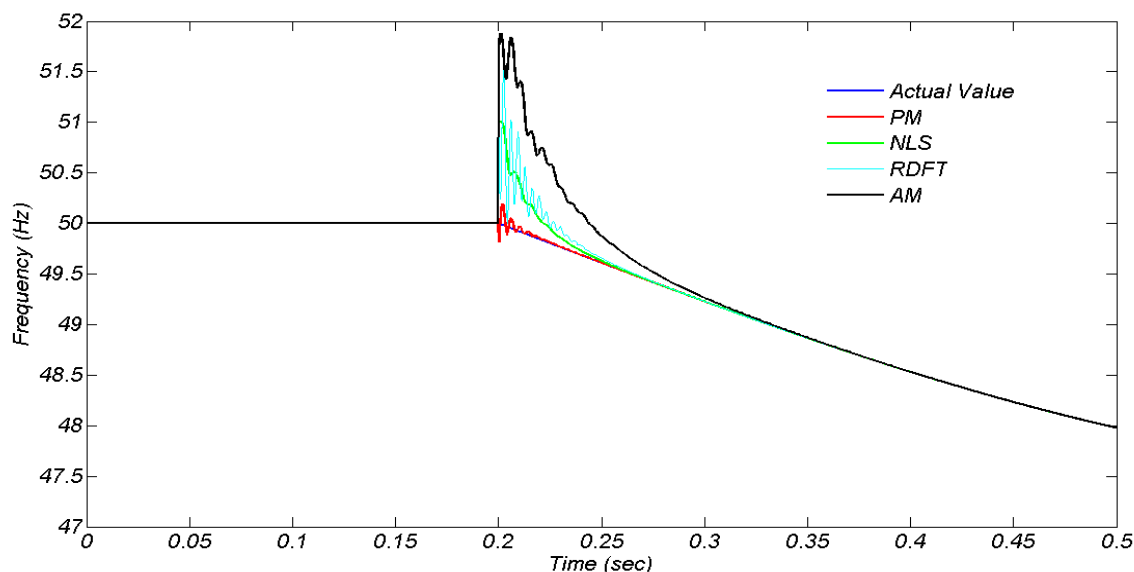


Figure 12. Impact on Frequency during first cycles after fault occurrence

Unlike conventional methods, proposed method has ability to remove transeint component created by CCVT. The CCVT transient components have significant affect to the result of the present methods which causes more instability in result. According to comprehensive fault simulations under numerous fault conditions, the proposed method was practical in terms of the numerical relay design. All of the above-mentioned results obviously demonstrate that the proposed method can precisely estimate frequency. Additionally, the proposed method has faster convergence and more precision in comparison with the existent frequency estimation methods.

## 5. CONCLUSION

The impact of transient behavior of CCVT on estimation of the fundamental voltage frequency, which is more important to some of the numerical protective relays, was described in this paper. The transient behavior of instrument measurements causes incorrect estimation within the first few cycles after a fault occurrence have been neglected in fundamental frequency estimation methods. Therefore, the protective system operates incorrectly. The proposed Frequency estimation algorithm was described, developed, demonstrated by a method which is based on Least square error. In order to increase phasor and frequency estimation accuracy, transient behavior of the CCVT, including knowledge of design and the connected burden was applied in Frequency estimation algorithm. This improved the frequency estimation. In order to validate of proposed method many dynamic tests were studied in PSCAD/EMTDC and method performances are shown in simulation results. The results show considerable improvements in precision and also speed convergence. Accordingly, the proposed method is very effective for fundamental frequency estimation of power system signals.

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