Realistic Testing Procedure of Voltage Transformer Failure Function

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Abstract
Power systems have a lot of tend to the fault. These faults are always detected and cleared by protection relays. Protective relays for the implementation of various protection algorithms, require to know the condition of the voltage and current electrical quantities. These quantities are very large in Sub Station, which is why these quantities reduce by using voltage and current transformers and then sends for relays. Existence of wrongs in the voltage transformer can cause the mal-operation of the relay and get out a healthy line of the network. To prevent such an occurrence, there is monitoring unit for the voltage transformers fail that are known as voltage transformer fuse failure (vtff) monitoring too. This protective function requires practical testing at all stages of development, commissioning, operation and maintenance. In this paper, the authors attempted to test the VTFF relay function using the AMT-105 relay tester device made by Vebko Amirkabir.

Keywords: Voltage transformer, Fuse failure, Power system protection, Relay test.

NOMENCLATURE

R_{C1}	Resistance of The first capacitor
C_1	Capacity of the first capacitor
R_{C2}	Resistance of The second capacitor
C_2	Capacity of the second capacitor
R_1	Resistance of the primary coil
R_2	Resistance of the secondary coil
R_t	Resistance of the regulatory reactor
L_1	Inductance of the primary winding
L_2	Inductance of the secondary winding
L_t	Inductance of the regulatory reactor
L_m	EMU core magnetizing
R_m	EMU core-less equivalent resistance
Z_b	Load impedance connected to the secondary terminal
N_1	Number of primary winding turns
N_2	Number of secondary winding turns
Φ_1	Primary coil leakage flux
Φ_2	secondary coil leakage flux
Φ_m	The main flux that circles the core and according to Faraday's law, it induces a voltage
α	Ratio of transformer

1. Introduction

Protective systems always plays a very important role in the stability of power systems. These protective systems need to know the condition of the voltage and current quantities to perform their task correctly. But since the quantities of these parameters are too high in the substation and transmission lines, and direct access to them is non-economic and non-practical, therefore, voltage and current transformers are used. The secondary of these transformers provides low-volume samples of the quantities which largely have all the characteristics of the original quantity, and all measuring and protection devices designed for low voltage and low-current levels, through them, they reach to the quantities required at the energy transfer station.

Capacitor Voltage Transformer (CVT) is a type of voltage transformer that is widely used in electrical energy transmission systems for voltage measurement (Huang, Liu et al. 2008). These types of transformers are usually designed as standalone single-phase units (Davarpanah, Sanaye-Pasand et al. 2012). CVT transformers are most used at high voltages above 145 kV. Inductive voltage transformers are most economical up to a system voltage of approximately 145 kV and capacitor voltage transformers above 145 KV (Sjövall 2005). With all the mentioned specifications, CVTs sometimes have problems and voltage signals are not sent correctly to the relay (Huang, Liu et al. 2008).

Article (Huang, Liu et al. 2008) divides voltage distortion CCVTs into two general groups. The first group discusses transient overvoltage due to switching operations or faults of line. The second group discusses overvoltage with a high-frequency component (Kezunovic, Kojovic et al. 1992, Fernandes Jr, Neves et al. 2001, Fernandes Jr, Neves et al. 2003). This incorrect measurement of the occurrence of problems within the CCVT or its secondary circuit results in wrong measurement of the voltage by the relays, and as previously mentioned, can lead to the loss of a single line of network. Losing a line in high-voltage transmission lines in special situation can cause network instability and causes black outs. These black outs can bring a lot of financial losses to energy transmission companies. To prevent such an occurrence in the relay, the monitoring unit for the failure of voltage transformers, known in some relays as voltage transformer fuse failure (VTFF), is responsible for detecting the reliability of the input voltage to the relay. Protective relays must have general requirements such as correct diagnosis of the problem, response speed and minimization of disturbances in the power system (Horowitz and Phadke 2008). These factors can have a severe drop in a protective relay due to their long operation in power system. This decline in the general requirements of the protection relays does not indicate before fault occurrence in the transmission lines. For reasons mentioned above, protection relays require different tests during of development, commissioning, operation and maintenance (Musaruddin, Zaporoshenko et al. 2008). In order to ensure the correct operation of the VTFF detection algorithms, it should perform appropriate tests in this regard. In this paper, the authors implemented the test using the Vebko Amirkabir AMT-105 relay tester device and analyzed the results of the VTFF function test.

2. Capacitor Voltage Transformer

To better understand the operation and test of the VTFF, we first need to get to know the interior structure and CVT equations. Generally CVTs are in two section, consist of capacitor voltage divider (cvd) with two capacitance called C1 and C2 and one electromagnetic unit (EMU). The capacity quantities of c1 and c2 are determined relative to the CVD input voltage. EMU includes an induction voltage transformer and a regulator and protection against Ferro-Resonance (Sjövall 2005). Figure 1 shows the equivalent circuit of a CVT.

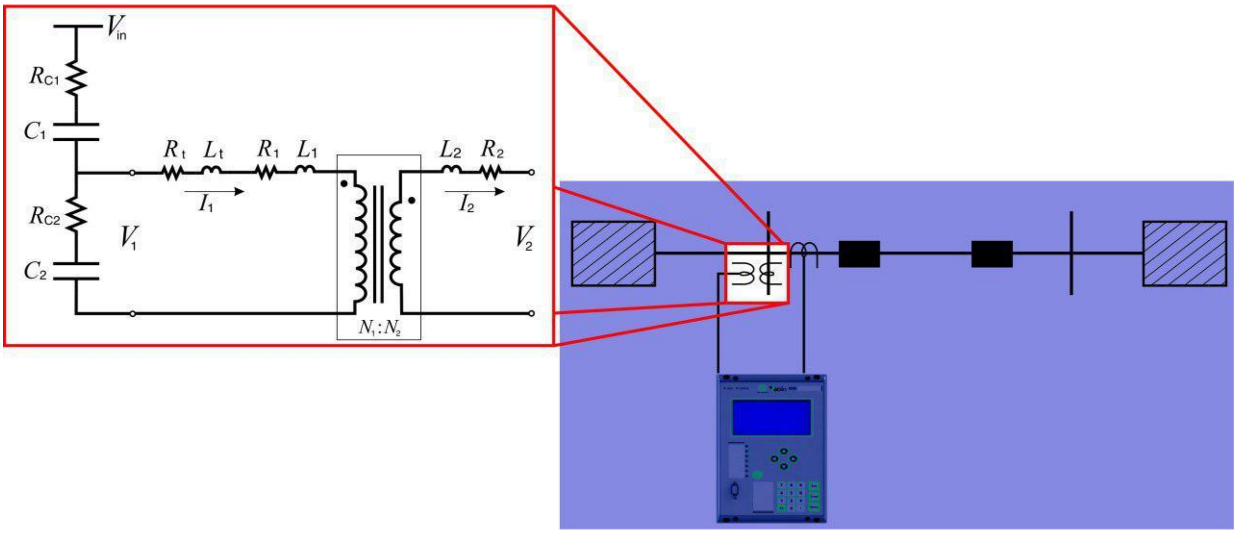

Figure 1: equivalent circuit of the CVT.

The CVD section contains two capacitors c1 and c2. The voltage reduction in CVD is based on Formula 1 (Sjövall 2005):

$$V_1 = \frac{\frac{1}{j\omega C_2}}{\frac{1}{j\omega C_1} + \frac{1}{j\omega C_2}} \times V_{in} = \frac{C_1}{(C_1 + C_2)} \times V_{in} \qquad (1)$$

Figure 2 shows the CVD equivalent circuit.

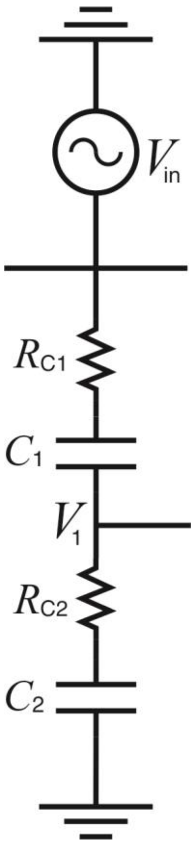

Figure 2: equivalent circuit of CVD.

The EMU section includes a single-phase transformer. In the single-phase transformers, L1 and L2 are obtained by following equations (Sen 2007):

$$L_1 = \frac{N_1.\Phi_1}{i_1} \tag{2}$$

$$L_2 = \frac{N_2.\Phi_2}{i_2} \tag{3}$$

Figure 3 shows the equivalent circuit of a single-phase transformer. To simplify the transformer's analysis, it is necessary to transfer electrical quantities to the primary or secondary sides. Transfer of electrical quantities in the transformer is done using the transformer ratio.

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \alpha \tag{4}$$

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} = \frac{1}{\alpha} \tag{5}$$

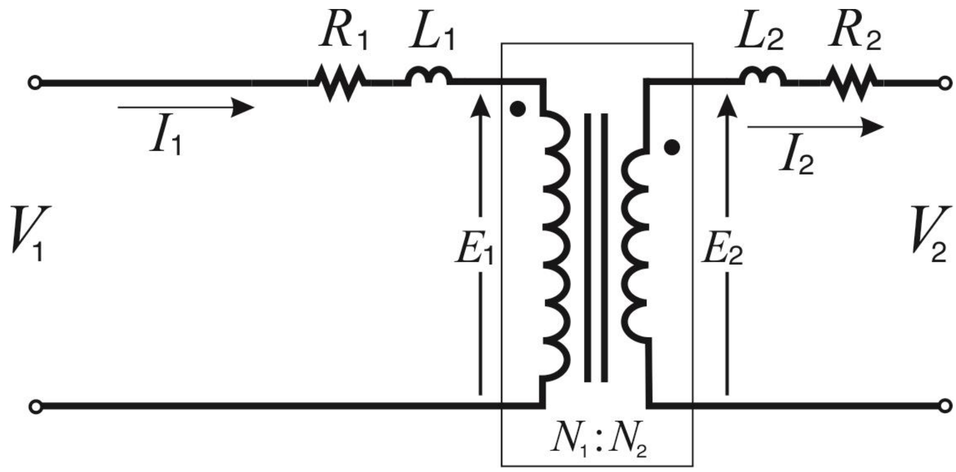

Figure 3: The equivalent circuit of a single-phase transformer (Sen 2007).

Figure 4 shows the equivalent circuit of the transformer by transferring the electrical quantities from the secondary to the primary side.

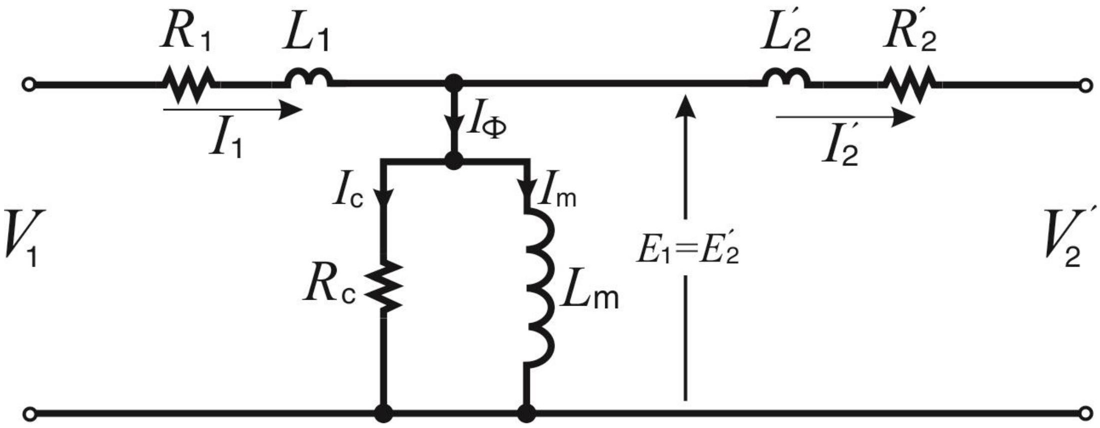

Figure 4: The equivalent circuit of a single-phase transformer with electric quantities transferred to the primary side(Sen 2007).

The equations for the figure 4 circuit are presented for transfer of electric quantities (Sen 2007):

$$E_1 = E_2^{'} = \alpha E_2 \quad (6)$$

$$V_2^{'} = \alpha V_2 \quad (7)$$

$$I_2^{'} = \frac{I_2}{\alpha} \quad (8)$$

$$L_2^{'} = \alpha^2 L_2 \quad (9)$$

$$R_2^{'} = \alpha^2 R_2 \quad (10)$$

In Figure 5, the equivalent circuit of CVT is shown with the transferred electrical quantities.

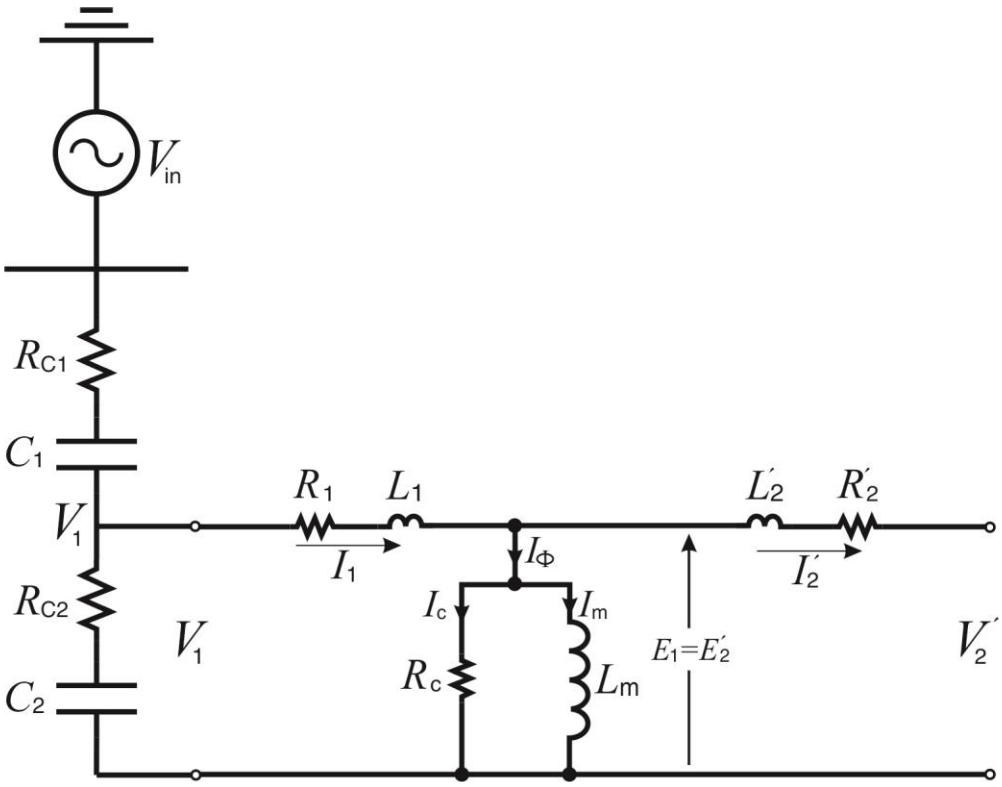

Figure 5: CVT equivalent circuit with transferred electrical quantities (Sen 2007).

For simplify the calculation of the equivalent circuit above, after the CVD section is expressed according to Figure 6.

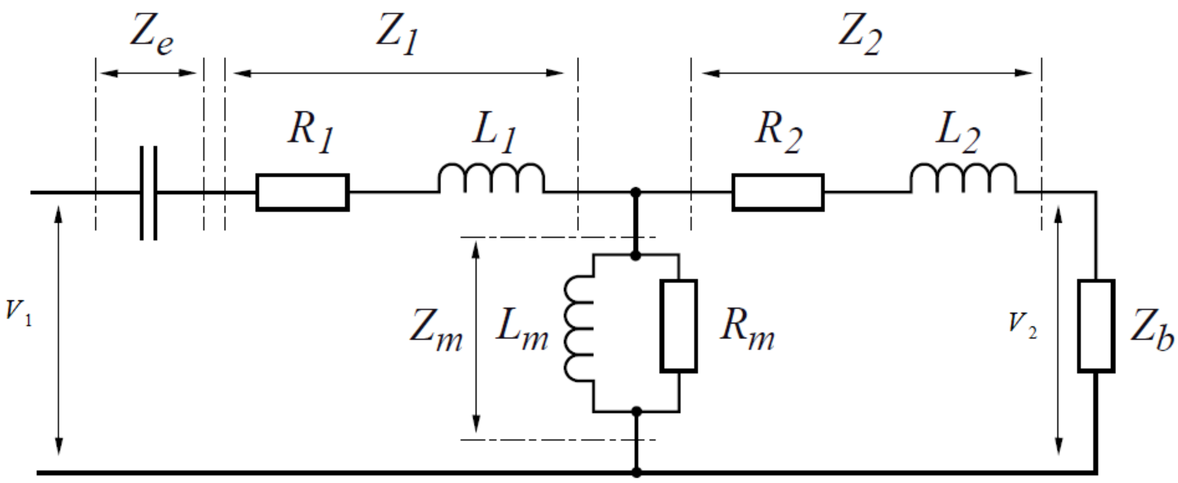

Figure 6: Simplified CVT equivalent circuit (Sjövall 2005).

The equivalent impedances are obtained from the following equations according to figure 6(Sjövall 2005):

$$Z_1 = R_1 + jX_1 \Rightarrow X_1 = j\omega L_1 \quad (11)$$

$$Z_2 = R_2 + jX_2 \Rightarrow X_2 = j\omega L_2 \quad (12)$$

$$Z_m = \frac{R_m + jX_m}{R_m \times jX_m} \Rightarrow X_m = j\omega L_m \tag{13}$$

$$Z_e = \frac{\frac{1}{j\omega C_1} + \frac{1}{j\omega C_2}}{\frac{1}{j\omega C_1} \times \frac{1}{j\omega C_2}} = \frac{1}{j\omega C_1 + C_2} \tag{14}$$

The relation between v1 and v2 is expressed in the following equation (Sjövall 2005):

$$V_2 = \frac{Z_m}{Z_m + Z_1 + Z_e} \times V_1 - \left[Z_2 + \frac{Z_m (Z_1 + Z_e)}{Z_m + Z_1 + Z_e} \times I \right] \tag{15}$$

Also, the amplitude and phase error in CVTs is obtained from the following equation (Sjövall 2005):

$$\varepsilon_0 + j\delta = \frac{V_2 - V_1}{V_1} = \frac{Z_1 + Z_e}{Z_m + Z_1 + Z_e} \tag{16}$$

3. Detection algorithm of CVT failure in protective relays

If the measuring voltage failure results from a wrong quantity in the secondary side of CVT system, the voltage element is not properly measured and can cause the mal-operation of relay in the following sensitive protection (Siemens 2012):

1. Directional overcurrent protection
2. Voltage controlled inverse time Non-Directional overcurrent protection
3. Under voltage protection
4. Distance protection
5. Etc

This false signal can also cause to mal-operation of Synchronization. CVT secondary faults include single-phase, two-phases, and three-phase faults. In the single-phase and two-phase faults of the system, there is a significant negative sequence voltage. However, these faults do not have an effect on the current, and this leads to a clear distinction of asymmetry between power system quantities (Siemens 2012).

If the negative sequence system is relative to the current positive sequence system, the following rules apply the Fault-Free case (Siemens 2012):

$$\frac{V_2}{V_1} = 0 \tag{17}$$

$$\frac{I_2}{I_1} = 0 \tag{18}$$

If a fault occurs in the secondary of voltage transformer, the following rules apply to single-phase fault (Siemens 2012):

$$\frac{V_2}{V_1} = \frac{0.33}{0.66} = 0.5 \tag{19}$$

$$\frac{I_2}{I_1} = 0 \tag{20}$$

$$\frac{V_2}{V_1} > \frac{I_2}{I_1} \tag{21}$$

The following rules also apply for two-phase fault (Siemens 2012):

$$\frac{V_2}{V_1} = \frac{0.33}{0.33} = 1 \quad (22)$$

$$\frac{I_2}{I_1} = 0 \quad (23)$$

$$\frac{V_2}{V_1} > \frac{I_2}{I_1} \quad (24)$$

In the event of single or two phase fault in the primary side of CVT, the current also displays a negative sequence system of 0.5. As a result, the voltage monitoring function is not responsive, because there is no fault in the CVT.
In order to prevent excessive estimation of the measurement voltage due to inaccuracy, the operation in more and less than the threshold value of the positive sequence systems of voltage ($V_1 < 0.1 < V_{nom}$) and current ($I_1 < 0.1 < I_{nom}$) is blocked [10].
A three-phase fault in the secondary side of CVT can not be detected through a single-phase and two-phase fault detection system. The monitoring of the progress of current and voltage overtime is required here. If the voltage reaches zero or be equall zero and the current remains unchanged, a three-phase fault occurs in the secondary side of CVT system. The sensitivity of the jump detection for current can be increased parameter FFM (3ph) (Siemens 2012).

4. VTFF Function Testing Techniques

The occurrence of a problem inside the voltage transformer (VT) or its secondary circuits will lead to a voltage wrong measuring by the relays. As a result, the protective functions that operates on the voltage (such as the distances and under voltage protection) may incorrectly detect the fault conditions and sends an incorrect trip command.

4.1. Preparing the conditions of VTFF unit testing

To perform tests related to the VTFF unit, first do the following wiring. To ensure the wiring and sequence of phases, compare the injected voltage and current with the displayed values on the relay. In order to check the correctness of the sequence of phases, the values should be injected with a difference of 10%. Establish connections for the test as in Figure 7.

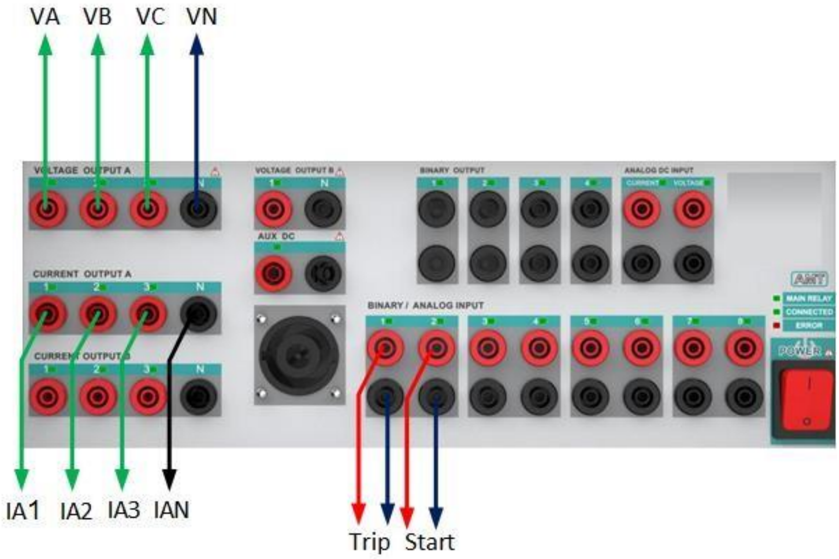

Figure 7: Connections to the VTFF monitoring unit testing.

4.2. The purpose of the VTFF monitoring unit testing

The purpose of the VTFF monitoring unit testing is to check the operation of this unit to detect the unreliable of the relay input voltage signal and to block the related protective functions.

4.3. The method of VTFF monitoring unit testing

The voltage transformer supervision (VTS) unit must be able to detect the unreliable voltage signal in the following four states:
1. unreliable voltage of one or two phases
2. Three-phase voltage is disconnected
3. The lack of the voltage of three phases in switching time of line
4. Blocking the protection function when receiving MCB Fail Auxiliary contact

For each of the above states, tests should be considered and the operation of the VTS unit should be checked. It was also necessary to test the contradiction of the condition to ensure that the logic of the monitoring unit was correct.

4.3.1. One or two phase voltage unreliabling test

For testing, two states must be set to Normal and Fuse Failure respectively in the AMT software(AMT-105 tester divise made by Vebko Amirkabir company) . In the first state, it should simulate the normal condition of the network, which should inject the nominal voltage and 20% of the CT current. The injection time of this state is at least one second. In a second state, the conditions for the fail of the single or two-phase of voltage transformer should be simulated. In this case, the voltage of one or two phases should be set to zero. The phase and amplitude of the three-phase current must be calculated in such a way that the zero or negative sequence current value (based on using the logic of the zero or negative component set in relay) is less than 300A primary side at the voltage level of 400 kV and 200A primary side At a voltage level of 200 kV. The duration of the injection of this state must be at least 1.2 equal to the maximum duration of the protective unit trip time, which is sensitive to voltage reduction (such as a distant and under voltage functions). Whenever the VTS blocking signal condition changes from zero to one and does not trip the voltage-sensitive functions, this state should be stop and the amount of time must be record at that instant.
The summary of the above description is shown in Figure 8.

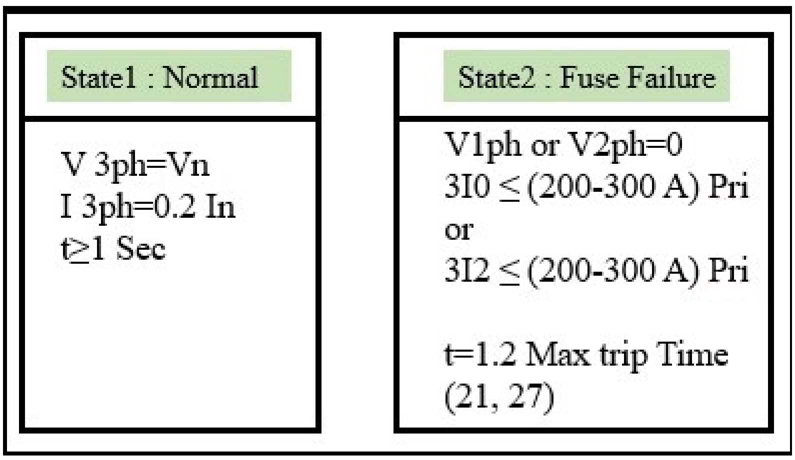

Figure 8: States of unreliabling one or two phase voltage Testing.

Another complementary test to be done is about releasing the VTS signal that its will be in normal mode. After the condition of the false voltage signal persists for more than a certain time, the VTS signal is locked in active condition, and then it should create a normal state that, after a specified time that is presented in the Technical Data of the relays, the signal VTS changes to zero.

4.3.2. False voltage signal test for three phases

As in the previous section, in order to simulate Normal and Fuse Failure, two states must be created. The first state should be in accordance with the normal state specification of the previous section. In the second state, the Fuse Failure conditions must be created to disconnection the voltage of the three phases, and the voltage of all three phases should be injected as zero.

In this state, the current of all three phases must be the same as the previous test. The injection time of this state must be at least 1.2 equal the maximum duration of the protective unit's trip time, which is sensitive to the voltage reduction, (Similar to the distant, under voltage function and etc). When the VTS Blocking signal changed from zero to one and did not provide the functions that are sensitive to the voltage reduction, This state should be stopped and the amount of time recorded at that moment. The summary of the above description is shown in Figure 9.

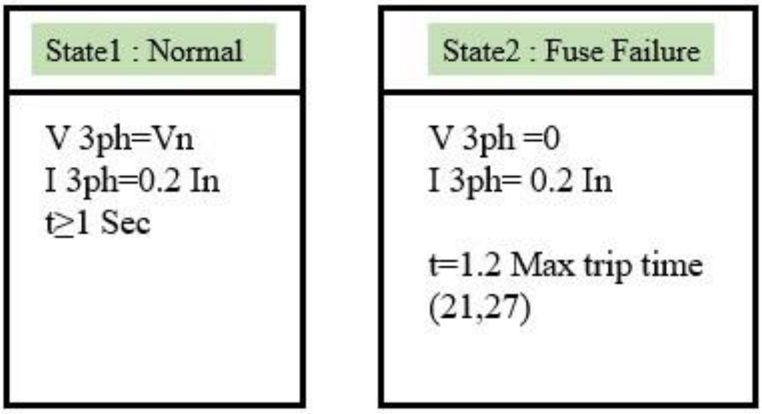

Figure 9: States related to the voltage unreliability test for all three phases.

Another complementary test to be done is about releasing the VTS signal that its will be in normal mode. After the condition of the invalid voltage signal persists for more than a certain time, the VTS signal is locked in active condition, and then it should create a normal state that, after a specified time, the signal VTS changes to zero.

4.3.3. Blocking the protective function by receiving an MCB Fail Auxiliary contact

In this test, as in the previous sections two states is simulate for Normal and Fault states. The first state should be in accordance with the normal state specification of the previous sections. In the second state, as in the previous section, a distance or under voltage fault should be considered and, at the start time of this state, MCB Fail signal be given by the outputs of the tester to the relay input. These functions should be blocked for the maximum duration time for the state and not send a trip command. The summary of the description above is shown in the figure below.

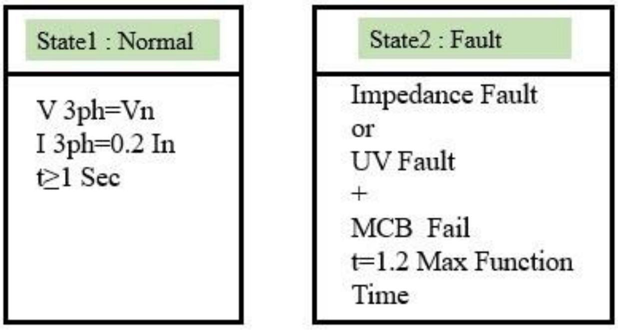

Figure 10: States related to Blocking the protective function with MCB Fail Auxiliary contact

4.3.4. Monitoring Unit VTFF Test Assessment

In all performed tests above, if the Fuse Failure condition is created for different situations, The VTS function must be operate, and in addition to the VTS signal, it must block the protective functions related to voltage And if the voltage returns to its normal value, the VTS signal must be zeroed and the protective function must be get out from the blocking condition.

5. Practical testing

For the practical testing of this function, according to the previously eexplanation, and with the relay setting, the requirements settings are made on the relay tester device. Figure 11 shows the states designed to the test of this function. The next step is the test of this function by injecting the voltage and current to the relay. Figure 12 shows the Fuse Failure function practical test.

As shown in Figure 12, after the voltage and current injecting to the relay and detection the failure of the CVT by the relay, the signal is transmitted to the tester device by one of the relay outputs that is specified previously in the relay. The LED also lights up.

	S1			S2		
Name	State 1			State 2		
V L1-E: V L1-E	63.51 V	0.00 °	50.00 Hz	0.000 V	0.00 °	50.00 Hz
V L2-E: V L2-E	63.51 V	-120.00 °	50.00 Hz	63.51 V	-120.00 °	50.00 Hz
V L3-E: V L3-E	63.51 V	120.00 °	50.00 Hz	63.51 V	120.00 °	50.00 Hz
I L1: I L1	200.0 mA	0.00 °	50.00 Hz	700.0 mA	0.00 °	50.00 Hz
I L2: I L2	200.0 mA	-120.00 °	50.00 Hz	200.0 mA	-120.00 °	50.00 Hz
I L3: I L3	200.0 mA	120.00 °	50.00 Hz	350.0 mA	120.00 °	50.00 Hz
Bin. Out.	B1. B2. B3. B4.			B1. B2. B3. B4.		
Trigger		1.000 s			210.0 ms	
Type	Normal			Normal		
Comment						
Bin. Input	C1 Trip			C1 Trip		

(a)

	S1			S2		
Name	State 1			State 2		
V L1-E: V L1-E	63.51 V	0.00 °	50.00 Hz	0.000 V	0.00 °	50.00 Hz
V L2-E: V L2-E	63.51 V	-120.00 °	50.00 Hz	0.000 V	-120.00 °	50.00 Hz
V L3-E: V L3-E	63.51 V	120.00 °	50.00 Hz	0.000 V	120.00 °	50.00 Hz
I L1: I L1	200.0 mA	0.00 °	50.00 Hz	200.0 mA	0.00 °	50.00 Hz
I L2: I L2	200.0 mA	-120.00 °	50.00 Hz	200.0 mA	-120.00 °	50.00 Hz
I L3: I L3	200.0 mA	120.00 °	50.00 Hz	200.0 mA	120.00 °	50.00 Hz
Bin. Out.	B1. B2. B3. B4.			B1. B2. B3. B4.		
Trigger		1.000 s			210.0 ms	
Type	Normal			Normal		
Comment						
Bin. Input	C1 Trip			C1 Trip		

(b)

Figure 11: (a) One phase testing, (b) Three phase testing

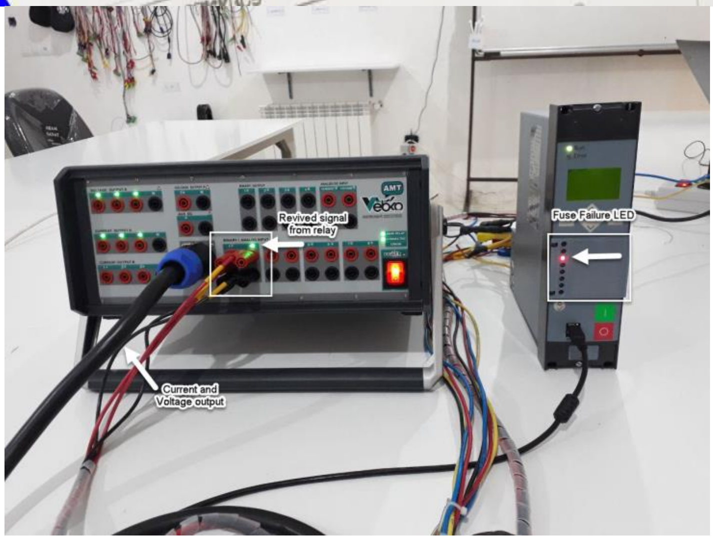

Figure 12: VTFF Testing

6. Conclusion

Voltage transformers are more important in power systems. Sometimes, due to the various factors, these equipments may have problems and thus do not send the properly signal to the relay. This false signal can cause a mal-operation of the protective relays. The mal-operation of the protective relays can always undermine the stability of a power system and inflict heavy damages on energy transmission companies. In the protective relay, the Fuse Failure function is used to prevent such an event. Protective relays, like any other equipment, may also be in wrong. For this reason, these equipment require periodic testing. In this paper, we investigate the voltage transformer and the Fuse Failure practical function test.

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