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Effect of Power System Dynamics on Transformer Differential Relay Sensitivity

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ABSTRACT

Differential protection is a type of protection scheme used in power system to protect generators, transformers, busbars, lines, feeders, etc. against internal faults. The protection principle is based on the comparison of the current entering and leaving the protected equipment, the differential relay gives a signal trip to the circuit breakers to isolate the protected equipment. This paper demonstrates the effect of the power system dynamics running voltage and frequency on transformer differential relay sensitivity, beside malfunction other errors due to, current transformers ratio mismatch, phase displacement, tap changer steps changes, dielectric losses due to stray capacitors, inrush current, transformer temperature, stray losses in transformer tank, transformer loads, or the relay will operate incorrectly in case of external faults with current transformer failure due to saturation or incorrect polarity.

Keywords: Differential, slope, Sensitivity, system dynamics Transformer tap changer, Stray losses, Over excitation, Inrush current, Stray capacitance, Current transformer.

1 INTRODUCTION

Electrical transformers are used to convert between different voltage levels in the electrical network, and they are used in the production, transmission, and distribution of power systems, their importance comes directly after generators in electrical networks due to the wide spread of transformers, they are protected from internal and external faults by relays that operate to give a warning or/and tripping signal in the event of faults, to disconnect the circuit breakers to isolate the fault zone to protect the transformer [1], voltage and current transformers are used to convert the high values of voltage and current to low values suitable to the relay. The protections installed on transformers vary according to their capacity, as fuses in small-capacity transformers are sufficient, and the level of protection increases with the capacity of the transformer, its importance, and its location in the electrical power system. As a result of the wide variety of transformer faults, there are many electrical, mechanical, thermal and gas protections, such as Buchholz relay, winding and oil temperature, pressure relief, sudden pressure, overcurrent, earth fault, short circuit and differential protection [1-6]. The transformer's differential protection measures the current entering the transformer I_1, and the current exiting the transformer I_2, and the operating coil of the protection device works by the difference between the two currents (I_1-I_2). In the case of normal operation of the transformer or a fault outside the protected zone specified by the current transformers i.e. external fault, the two currents are approximately equal, and the difference between them is close to zero and the relay will not be operate, in the case of an internal fault in the power transformer or inside the protected zone the differential protection device will be operate, where the current difference between the incoming and outgoing will pass through the operating coil of the protection device as shown in fig. (1), where there is a slight difference in the incoming current and the outgoing current in relay operating coil during normal operation or an external fault, the device may be led to incorrect operation in case of external faults with current transformer failure due to saturation or inrush current or a sympathetic inrush current and other reasons [4-11].

2 REASONS LEADING TO UNEQUAL INLET AND OUTLET CURRENTS.

There are several reasons leading to the inlet and outlet currents are not equal, which leads to the possibility of incorrect operation of the relay such as mismatch between the CT ratios and the power transformer ratio, Variable ratio of the power transformer caused by a tap changer, phase shift between the power transformer primary and secondary currents for delta wye connections, magnetizing inrush currents, transformer overexcitation, current transformer saturation etc. [2-8] as demonstrated in the following.

First, because the current transformers are not exactly symmetrical, even if two current transformers have the same specifications and manufacture, the value of current and phase angle of the secondary winding differ slightly for the two transformers at the same value and phase angle for primary current of the two transformers.

Second, the accuracy of measuring of the current transformer depends on the value of the measured current, the accuracy of the measurement increases near the rated current of the current transformer and decreases at a small current value, also decreases greatly at the saturation of current transformer or at frequency less than rated [12]. Therefore, there is a slight difference in the value of current and displacement angle for the incoming and outgoing currents [12-15]. To prevent operation at higher currents without saturation we use special (class X) current transformer for differential protection where high knee points are require.

Thirdly, the presence of stray losses due to the stray magnetizing in transformer winding and dielectric losses due to the stray capacitance of the protected transformer as a result of the presence of connection cables or lines, insulators, insulating paper and oil in the space between the entrance and exit of the current transformers [16-19], C1 between the high-voltage winding and the medium-voltage winding, C2 between the high-voltage winding and the ground, and C3 between the medium-voltage winding and the ground as shown in fig. (2). As a result of the presence of the dielectric materials, there is a resistance that can be represented in parallel with the capacitive impedance as shown in fig. (3), theses currents will be passing through the current transformer at the primary side only of power transformer thus also producing a difference in the current value and displacement angle of the entry and exit current in the relay.

Fourth, saturation occurs on one side of the current transformers for differential protection as a result of the high starting current of high-power electric motors, as this current contains a DC component in the starting current, or due to high external fault current, which is sometimes sufficient to saturate one of the current transformers as the current of it will decrease by a large value in the secondary winding, to operate differential protection by error [2, 20].

Fifthly, when a large inductive load is suddenly disconnected, from the secondary side of the transformer and the primary is connected to the source, the voltage on this transformer will rise, and its magnetic flux will increase i.e. over excitation, then the current of the primary winding will increase strongly, may be creating saturation of the current transformer on the primary side [2-23] thereby increases the odd harmonics, where the Fundamental harmonic represents approximately 52%, the third harmonics approximately 26%, and the fifth harmonics within the delta connection to approximately 11%, and since the third harmonic and its double rotate within the delta connection of transformer and do not appear on the transformer terminals,

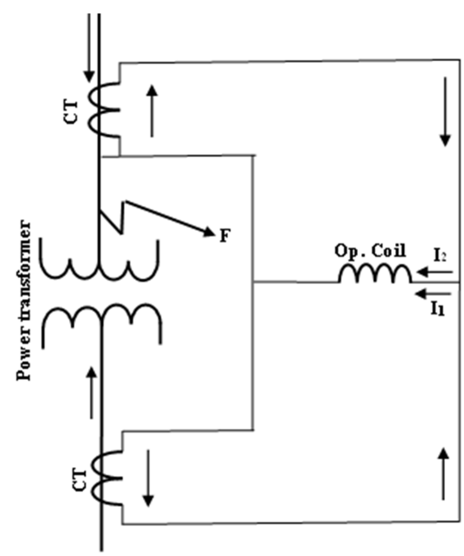

Figure 1: the currents in case of internal fault

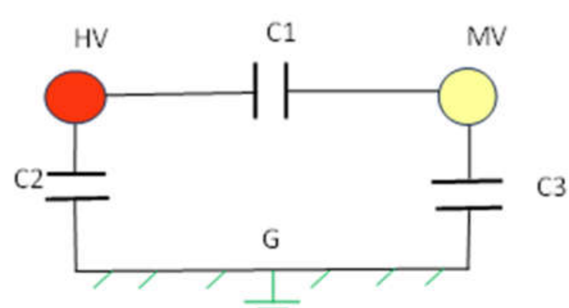

Figure 2: transformer capacitance representation

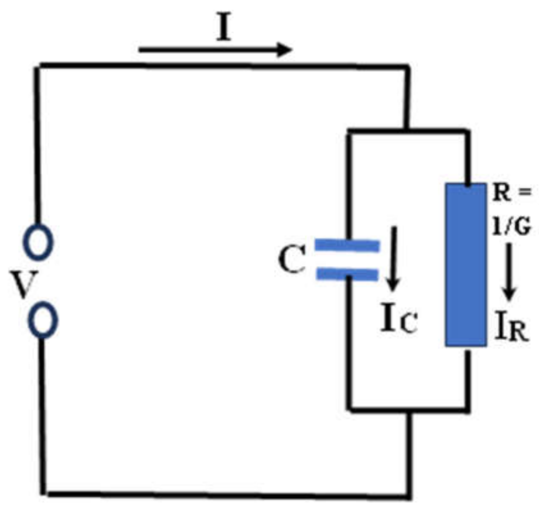

Figure 3: transformer dielectric capacitive impedance

Fifthly, when a large inductive load is suddenly disconnected, from the secondary side of the transformer and the primary is connected to the source, the voltage on this transformer will rise, and its magnetic flux will increase i.e. over excitation, then the current of the primary winding will increase strongly, may be creating saturation of the current transformer on the primary side [2, 20-23], thereby increases the odd harmonics, where the Fundamental harmonic represents approximately 52%, the third harmonics approximately 26%, and the fifth harmonics within the delta connection to approximately 11%, and since the third harmonic and its double rotate within the delta connection of transformer and do not appear on the transformer terminals, therefore, the increase in magnetic flux, over excitation is distinguished by the fifth harmonic from normal faults because its value increases when the magnetic flux increases in transformers directly connected to generators (Unit Transformer) or with high inductive loads, the voltage/frequency is measured for over excitation protection it depends on the fact that the flux is directly proportional to the generated voltage and inversely proportional to the frequency, where $\Phi \alpha V/F$.

Sixth, the difference between the primary and secondary current in the power transformer and using current transformers with appropriate conversion ratios as much as possible on both sides of the transformer, however there will be a difference in the primary and secondary currents at the relay (CT mismatch) [1, 2, 12]. This problem is overcome by using the closest appropriate values for the conversion ratios of the current transformers (CTRs) on both sides of the transformer, input TAPs for traditional protection device, dealing with the modern digital device software and by using auxiliary CT to reduce the error rate as much as possible.

Seventh, most power transformers are equipped with tap changers, some of which are changed on a load, which works to change the voltage consequently the current on the side of the transformer where the tap changer is located,

always towards the high voltage of the transformer without changing the current on the other side of the transformer, which creates a difference in current between the inlet and outlet current of the transformer differential relay [2], this is avoided by adjusting the CT ratio matching TAPs values in a traditional differential protection device, while choosing an appropriate slope to avoid the largest expected error, and it is corrected with modern digital devices by Software.

Eighth, the method of connecting three-phase transformers, as the value and phase angle are differ depending on the method of connection [2, 17], when connecting star-delta power transformers, this results in a phase angle shift between the current entering and the current exiting of the transformer, which requires connecting delta-star current transformers to avoid the effect of phase angle shift.

Ninth, the difference in polarity of current transformers is one of the reasons for incorrect disconnection in the differential protection of transformers [2]. The polarity of current transformers is taken into account when installing for the first time, after performing the maintenance and review process for the protective device circuits, to ensure the correctness of the connections in current transformers the point of entry of the current into the primary is the point of exit of the current into the secondary.

Tenth, the inrush current in the transformer can cause incorrect trip of the transformer, the reason for this problem is that when the power transformer is disconnected, a portion of the magnetic flux remains inside the iron core, which is called the residual flux ΦR it is value depends on the disconnecting moment of the transformer at the sine wave of magnetic flux, when the transformer is connected again, the moment of connection at the sine wave of the magnetic flux is different from the moment of disconnection, so the flux begins to appear high to compensate for the value of the remaining magnetic flux present at the moment of disconnection to draw a high inrush current to generate this high magnetic flux. However, if the moment of connection of the transformer is similar to the moment of disconnection, it does not need any additional flux to compensate for the remaining flux. Therefore, the normal flux current will be drawn without any increase, and the inrush current has no specific value, its maximum value is if the disconnection takes place at Φmax and the connection takes place at $-\Phi max$ or vice versa, and it disappears when there is no remaining magnetic flux, if the transformer connection moment is at the disconnection moment of the sine wave of the magnetic flux, or if the entry moment coincides with the maximum value of the sine wave of the voltage Vmax, in which the flux is as small as possible due to a 90° lag behind the voltage according to Faraday's law Φ α (dv/dt). The inrush current on the three phases of the transformer varies in shape and value for each phase depending on the moment of disconnection and connection and the value of the remaining flux for each phase, the value of the inrush current reaches from 5 to 20 times the rated current of the transformer and increases with increasing transformer capacity, it lasts about one second and its value decreases quickly until it reaches the normal current during that short period. This current only passes through the primary side of the transformer and does not pass through the secondary side, which may lead to a wrong transformer trip by the differential protection device due to a natural phenomenon of the iron core of the transformer not due to a real fault, also if there are two transformers connected in parallel and one of them is disconnected, a sympathetic inrush current occurs to the transformer in service when the other transformer is connected again and the value of the sympathetic inrush current is less than the value of the inrush current of the transformer that was connected, the duration of the presence of the two currents in the two transformers is greater than the duration of the presence of the inrush current when the transformer is connected alone i.e. the other out of service due to the increase in the time constant (L/R) in the case of the transformers being connected in parallel, where the value of (L) for the two transformers connected in parallel decreases from the value of (L) for the transformer alone, the DC component present in the inrush current of the transformer that has been connected increases the voltage drop on the source terminals of the two transformers, especially at the maximum value of the inrush current of the transformer that has been connected, which causes a current to pass with a negative sign, that is, in the opposite direction from the transformer in service to the source, the best way to protect transformers in this case is to use separate protection systems for each transformer separately not to use a single protection system for both transformers together, because in this case it requires more complex circuits to detect and avoid the problem [2, 26].

3 DIFFERENTIAL PROTECTIVE DEVICE SENSITIVITY.

To solve most of these problems, a modification was made to the protection device, where two other coils were added to the differential relay called restraining coils as shown in Fig (4). The number of turns of this coil is usually less than the number of turns of the operating coil, as the operating torque is proportional to the operating current $I_{op} = (I_1 - I_2)$ passing through the operating coil, the restraining torque is proportional to the restraining current $I_{res} = (I_1 + I_2) / 2$ passing through the relay restraining coils, if the operating torque exceeds the restraining torque, the relay will trip the transformer and vice versa, and the operating current must exceed a certain percentage of the restraining current, so it is called biased or percentage differential, the slope of this relationship is $K = (I_{op}) / (I_{res})$, which is often 10%, 20%, or 40%, this means that for the relay to work, the ratio of the operating current to the restraining current must be the slope as shown in fig. (5), and the sensitivity of the relay increases to trip for the smaller slope, that is, the expected percentage of error

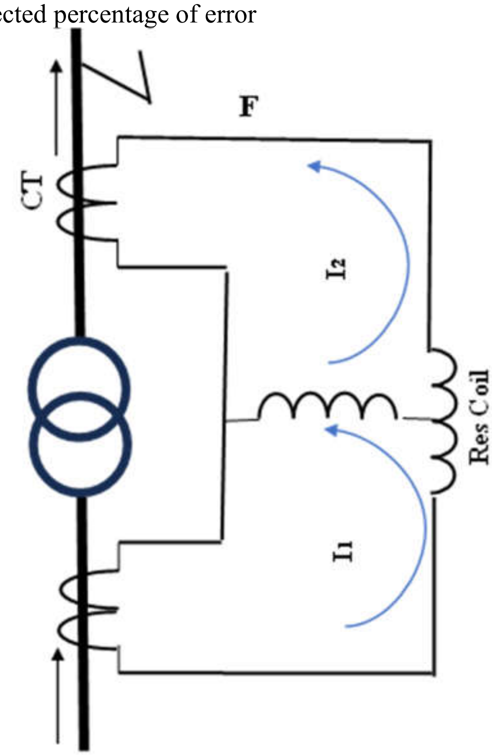

Figure 4: differential relay with restraining coils

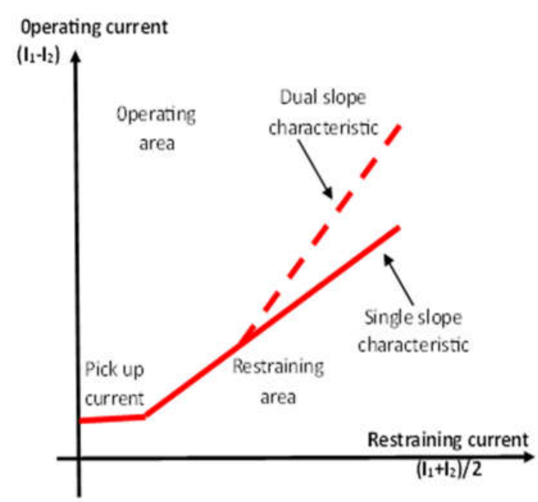

Figure 5: percentage differential relay Characteristic

from the asymmetry of current transformers etc.is smaller, the percentage of 10% in some devices represents 0.2 A. which is the lowest current at which the relay operates, and it is called minimum pickup current [1, 2]. The operating time in these traditional devices is between 25:150 ms, and in modern digital devices it is less than 2 cycles. There is a safety margin against incorrect operation of the relay and also to overcome friction in traditional devices, called the biased differential, which is the lowest operating current I_{op} at which the relay operates and is usually set within 0.25 A. When the small current difference results from the current transformer ratio mismatching error, the step of the tap changer of the transformer to be protected etc. The relay will not operate. In the event of internal fault in the transformer and it is fed from both sides, the total currents will pass through the operating coil because the current will reverse its direction in the second transformer, however, in the event that the transformer is fed from one side only, the current will be distributed between the fault and the load, where the current will decrease, but it will be sufficient to operate the relay, where the load current will not be reversed at the second current transformer, therefore the operating current will be the difference between the two currents and its value will be less than if the supply was from both sides [2]. Inrush current problem is overcome in two ways.

The first is to reduce the sensitivity of the protection device for a period of time after connecting the transformer. This is done by connecting a resistance in parallel with the operating coil of the protection device to reduce the current passing through the operating coil as shown in fig. (6). This resistance is controlled by a contact point of the under-voltage relay device. If the transformer is disconnected, the voltage drops and the contact point of the resistance is closed, when the transformer is connected, a part of the inrush current passes through the resistance, which reduces the sensitivity of the protection device to trip, the transformer voltage works in shortly time after connecting the transformer to disconnect the contact point and disconnect the resistance, the operating coil becomes operational with the required sensitivity to any internal fault of the transformer zone.

The second method is to use second harmonics to prevent the operation of the protective device, as the inrush current is rich in second harmonics, reaching 30-40% of the value of the current, while in real faults its value does not exceed 7% of the value of the current. Therefore, a filter was made for the second harmonic to send blocking signal if the second harmonic current is within the range of 10:20% of the value of the current, as this means that it is an inrush current not a fault current [2, 23-27], the blocking signal will not be sent in the case of small values of the second harmonic so that the relay works, whether it is traditional or digital. In case of over excitation current we use the fifth harmonics to send blocking signal to prevent incorrect transformer tripping i.e. the differential relay with harmonics restrain.

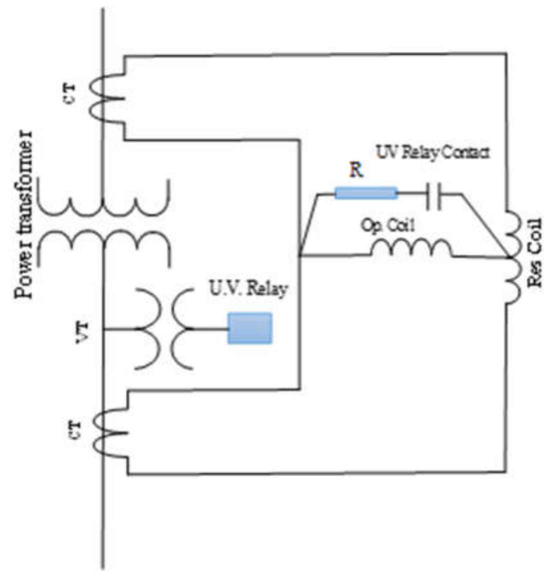

Figure 6: reducing the sensitivity of the differential relay for transformer inrush current

4 EFFECT OF POWER SYSTEM DYNAMICS ON DIFFERENTIAL RELAY SENSITIVITY.

A power system is continuously subjected to a variety of disturbances, these may vary from minor events like small and random load changes to major events like faults, generators tripping, if there is a sudden tripping of one or more of the generators in the electrical power system, the generated capacity becomes less than the load capacity, so the speed of all generators in the electrical network decreases and the frequency decreases accordingly until the speed regulators of the turbines work to increase the opening ratio of the turbine's steam feeding bluffs, thus increasing the electrical capacity, of all units participating in the system, as shown in fig (7), also the generator current, and reactive power will increase to maintain the generator voltage constant as shown in fig (8).

Also, if there is a sudden tripping of a line with a heavy load, the generation capacity will be greater than the load capacity, and this increases the speed of the turbines in the electrical power system, thus increasing the frequency. The regulators work to reduce the amount of steam entering the turbines, which works to reduce the frequency to the normal operating value as shown in fig. (9) for 150 MW unit at Abu-Soltan steam power plant also the reactive power, frequency, and generator current will increase, and the voltage and active power of the generators will decrease, as shown in fig. (10) for one of the steam unit generators, capacity 250 megawatts at West Damietta compound cycle power generation station. The distance of the faults from the stations and the capacity of the station affects the values of change in voltage, current, active and reactive power of the generators in the electrical power system, as the generators closest to the fault are affected faster than those farther away.

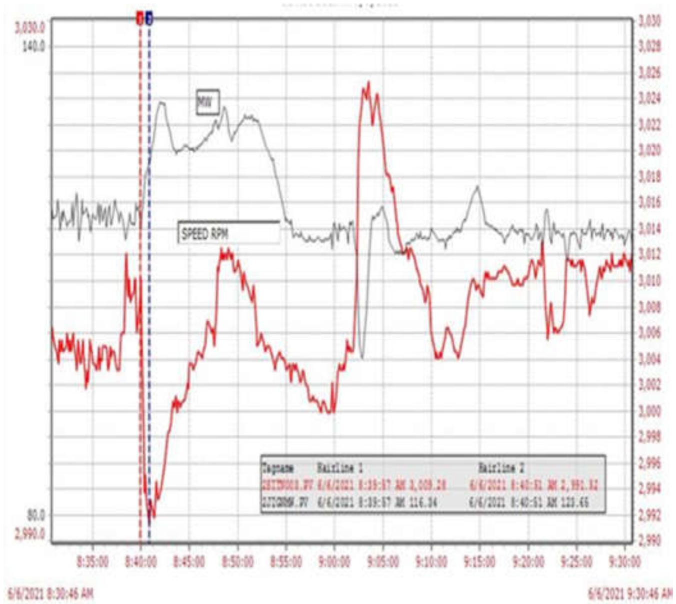

Figure 7: power system low frequency due to loss one of running generators

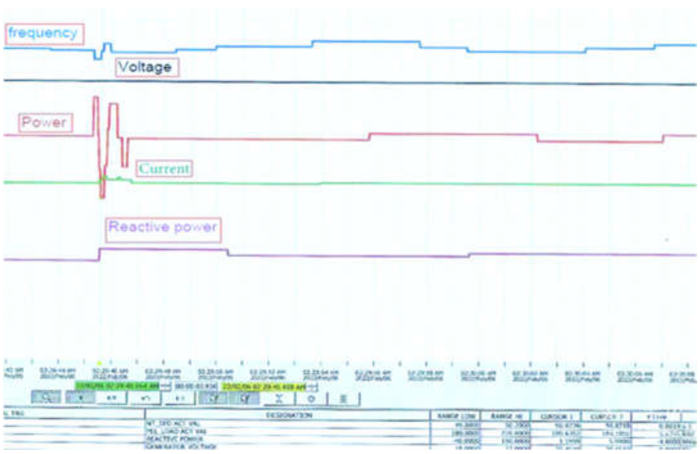

Figure 8: participating one of generators for active and reactive power of power system

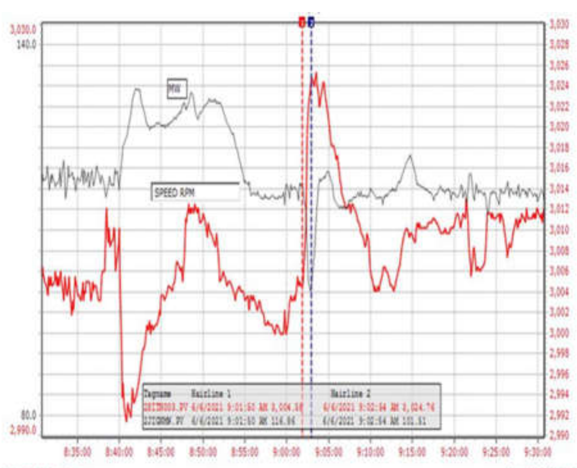

Figure 9: power system high frequency due to line loss with heavy load

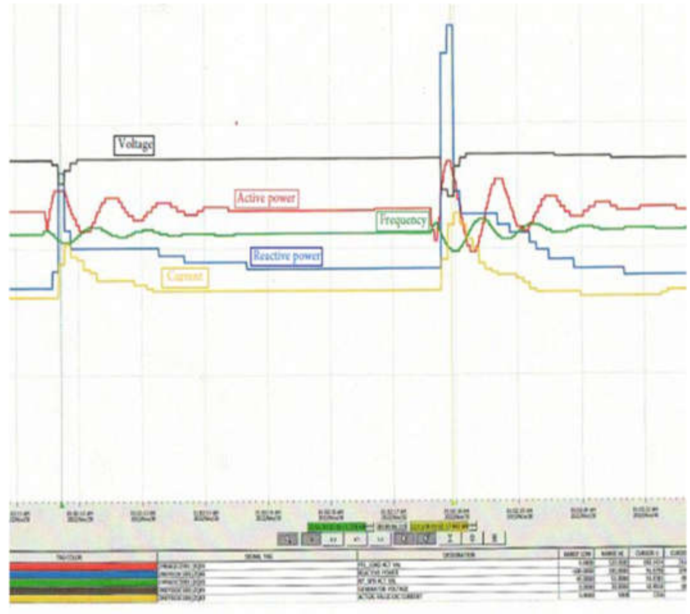

Figure 10: increase generator reactive power and power system frequency due to faulted line tripping

Also, during power system normal operation, the running voltage will increase due to the charging current for a high-voltage transmission line when a heavy reactive load is removed or reactive power generation higher than demand, or low frequency at rated voltage due to power system disturbance such as suddenly loss of some units during operation or connected heavy loads to the system, it is desirable that a power system settle to an acceptable steady state condition without exceeding equipment ratings. Consequently, the dynamic behaver of a power system has an important bearing on satisfactory system operation, so the continuous changes in power system voltage, frequency, temperature, active and reactive power are effect on the sensitivity (slope) value of the relay setting of power transformer differential protection, because when the running voltage increase at rated frequency or the running frequency decrease at rated voltage the core of transformer is subjected to over excitation $\Phi \propto V/F$ and the magnetizing current will increase, also the, transformer copper losses, current transformer burden at secondary side, connected cables, transformer insulators, current due to capacitance and resistance of the dielectric of transformer inside protective zone between input and output current transformers are affected by the changes in voltage, frequency, transformer loading and temperature, this current will be passing in the primary winding only of the transformer to make change in sensitivity relay (slope) setting.

5 EFFECT OF LOAD, TEMPERATURE AND TAP CHANGER.

In order to know the effect of load, temperature, and the step of the transformer's tap changer on adjusting the sensitivity of the transformer's differential protection device, we use the experiment results of measurement of load losses as shown in table (1) for a three-phase power transformer outdoor 186 (ONAN) - 248 (ONAF1)- 310 (ONAF2) MVA, with tap changer of 9 taps, Ratio: 220000 ± 4 *2.5 % / 15750 V, 50 Hz, vector group YNd1, the test was done using A.C power analyzer (NORMA D 6000 N° SO83435SS) by supply H.V side and short circuit on M.V. The test results were obtained at the temperatures shown in the table (1), while the resistance of the H.V winding, M.V winding and losses was calculated at the highest oil temperature, of the operation of the transformer which is 85.9 °C. From the results of the transformer load losses test, it is clear that the losses in the windings towards the high and medium voltage of the transformer increase with increasing load and temperature, as they are equal to the square of the current intensity multiplied by the resistance of the transformer winding, and current increases with increasing load, and the resistance of the winding increases with increasing temperature, while stray losses increase with increasing the total losses of strays and windings of the transformer, i.e. increase with increasing load and temperature, these losses are of current found only, also when the step of the tap changer is increased, this increases the number of turns of the transformer winding on the side where the tap changer is located, which is always in the side of the highest voltage and lowest current, so that the voltage increases and the current decreases on this side due to the transformer power is constant. So, the process of adjusting the sensitivity of the transformer's differential protection device increases the margin of error. The stray losses decrease with increasing temperature, where the resistance of transformer tank, insulators, etc. is increase with temperature to decrease the stray losses due to flux leakage, also insulating materials resistance decreases with increasing temperature. Changing the steps of the tap changer of transformer also affects the losses of the stray, medium and high voltage windings, the losses increase with increase of the step of tap changer as shown by the test results for measuring the transformer's load losses in table (1), where the currents of these losses pass through the current transformers located on the primary side only and do not pass through the current transformers on the secondary side, and these losses affects the sensitivity of the transformer's differential protection device.

Table 1. measurement of load losses.

Test values					Test result			
					Losses (KW)			
Tap step	Rated power	V (V)	I (A)	Temp (°C)	H.V	M.V	Stray	Total at (Ir)
1	310	26456	887.7	21.4	239.4	285.1	45.7	570.2
				85.9	299.6	356.8	36.5	692.9
	248	21882	734.3	21.4	153.2	182.5	30.1	365.8
				85.9	191.7	228.4	24.0	444.1
	186	16441	551.7	21.4	86.2	102.6	17.7	206.5
				85.9	107.9	128.4	14.1	250.4
5	310	30720	791.4	21.3	232.6	285.0	63.6	581.2
				85.9	291.2	356.8	50.8	698.8
	248	25274	651.0	21.3	148.9	182.4	40.3	371.5
				85.9	186.4	228.4	32.2	446.9
	186	19206	494.8	21.3	83.7	102.6	22.5	208.8
				85.9	104.8	128.4	18.0	251.3
9	310	36185	726.1	21.5	224.4	285.2	93.9	603.5
				85.9	280.7	356.8	75.1	712.6
	248	29364	587.0	21.5	143.6	182.5	58.9	385.0
				85.9	179.6	228.4	47.1	455.1
	186	22449	449.3	21.5	80.8	102.7	32.3	215.7
				85.9	101.1	128.4	25.8	255.3

6 EFFECT OF VOLTAGE AND FREQUENCY.

The effect of the change in voltage and frequency can be known by using the results of no-load loss test on the same transformer whose data was previously mentioned to obtain the power loss at no load at an average temperature of the insulation and cooling oil of 21.8 °C, by using AC power analyzer NORMA D6000 N° M831791RR, the test results are shown in table (2). The no-load current increases about four times and the no-load losses increase about one and a half times if the voltage increases within 10% of the rated voltage of the transformer fig (11), to increase the magnetic flux, because the iron core of the transformer is close to saturation, also this happens if the frequency decreases at the rated voltage, where the intensity of the magnetic flux is proportional to the voltage/frequency $\Phi \propto V/F$, and the no-load losses decrease slightly by increasing the temperature, as shown in table (2). The change in voltage, frequency, or temperature, i.e. electrical power system dynamics, causes a change in the current towards the source only, which causes a difference in the current transformers measuring the primary and secondary to affect the sensitivity of the transformer’s differential protection device. The test results show an increase in the fifth harmonic ratio of the no-load current at rated voltage and rated frequency as shown in table (3).

Table 2. no - load test.

V (V)	I (A)	P (KW)	
	Temp. (21.8 °C)		Temp. (35.9 °C)
14175	4.25	95.42	94.5
14904	4.93	109.2	
15750	6.56	130.88	129.7
16521	10.96	159.2	
17325	26.18	201.32	199.5

Table 3. measurement of harmonics of no-load current.

Harmonics	1= 50Hz	2	3	4	5	6	7	8	9
Percent value (%)	100	2.4	21.4	1.85	31.9	0.5	18.7	0.87	2.7

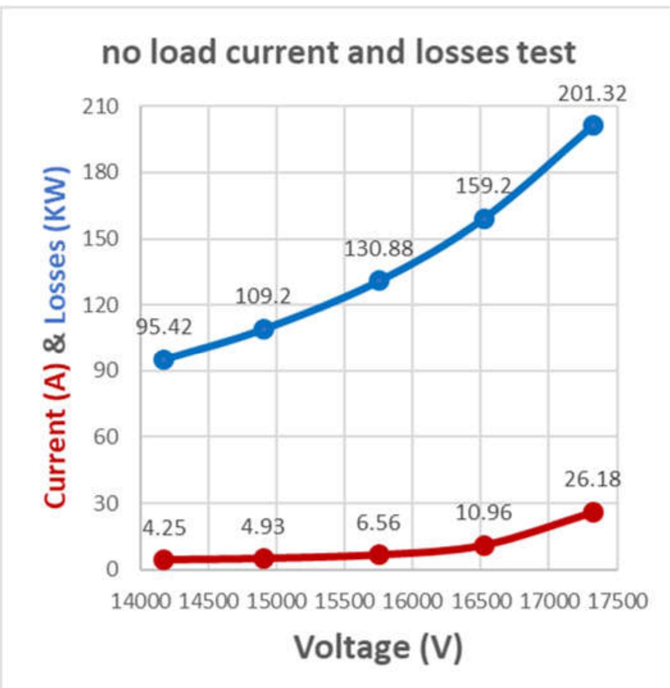

Figure 11: transformer no load losses test

7 UNIT TRANSFORMER OVER EXCITATION.

All transformers in the electrical power system are sometimes exposed to an increase in magnetic flux (over excitation) during normal operation as a result of an increase in voltage or/and a decrease in frequency due to the dynamics of the electrical power system, which exposes all transformers to an increase in the magnetization current (over excitation), so increase of the temperature of the iron core of the transformer, and increase in the temperature of the insulating paper of the transformer windings, which leads to a decrease in the degree of polymerization of the insulating paper, then decrease the transformer life time. However, the unit's transformers (main and auxiliary) connected directly to the generator are more exposed to an increase in magnetic flux because the generator of the unit before connected to the network, the generator voltage is built up, if the frequency is less than 47.5 Hz i.e. 95%, of the generator's rated frequency, therefore the under frequency protection will operate the lock out relay of generator, main and auxiliary transformer to trip the turbine and boiler of the unit fig (12) shows the network configuration for Abu-Sultan steam power plant, as the speed of the generator must be greater than 95% of the rated speed, sometimes while raising the speed, the rated voltage of the generator has been built up and the frequency has not reached the rated frequency, and in this case generator, main and auxiliary transformer will be exposed to over excitation as shown in fig (13) for one of generators at Abu-Sultan steam power plant during synchronizing. Also, it is possible to trip the generator without tripping the generator field breaker so the generator voltage still presents by frequency gradually decreases depending on the speed of the generator rotor due to the inertia, which works to increase the magnetic flux (over excitation) of the generator, main and auxiliary transformer together. Therefore, the degree of polymerization of the insulating paper for these transformers is lower than that of other transformers in the electrical power system for the same operating time. The study recommends that the generator voltage must be built up at generator speed compatible with the network as close as possible to the network running frequency, as well as creating two generator field circuit breakers connected in series, so that if the first breaker is not tripping during 300 ms from sending a trip signal i.e. fails to trip, then the breaker failure protection will send a tripping signal to the second breaker to trip.

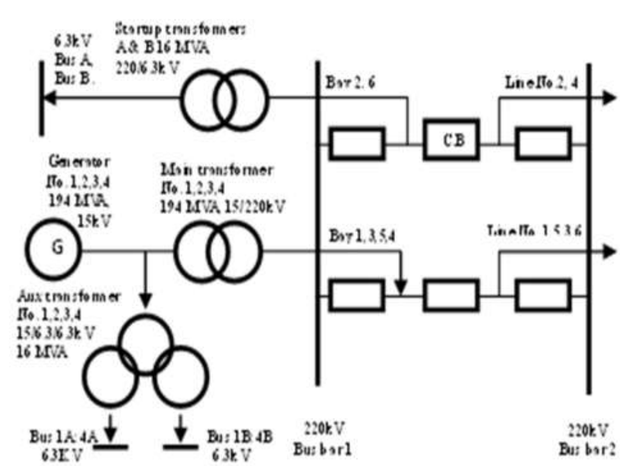

Figure 12: schematic diagram for unit transformer at Abu-Sultan steam power plant

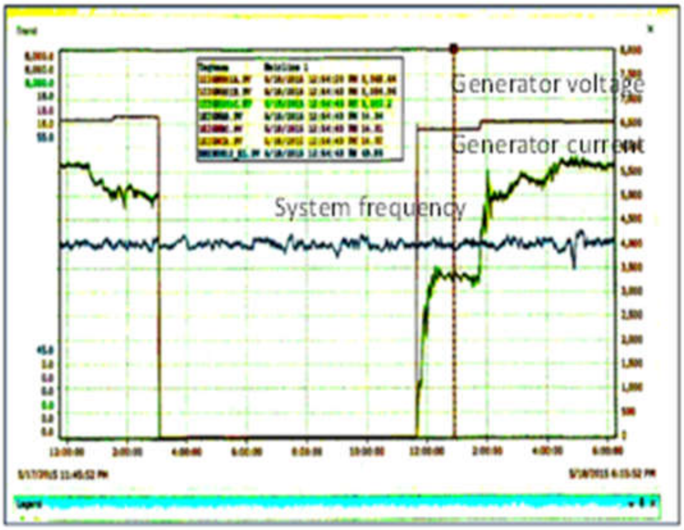

Figure 13: generator voltage, current and System frequency during shutdown and synchronizing in one of power plant

8 CONCLUSIONS

The operation of the protective device sensitivity changes depending on the conditions and variables of the electrical power system, such as changes in voltage, frequency, and temperature, which sometimes works to increase the magnetic flux and the excitation current in the transformer. Also, the sensitivity of the protective device is affected by the load loss currents in the transformer, which change depending on the load of the transformer and the change in the step of the voltage tap changer and temperature, most of these currents pass only in the primary side of the transformer to create a difference in the input current from the output current of the transformer, and thus a continuous change in the slope and sensitivity of the differential protection device of the transformer according to the conditions of the power system dynamics, the transformer load and the temperature i.e. The adjustment value of the slope decreases and the sensitivity of the differential relay to trip increases with the increase in the network voltage, transformer load, temperature, the step of transformer taps changer and the decrease in power system frequency. Also, the highest value of harmonics of the no-load current at the rated voltage and rated frequency is the fifth harmonic ratio due to magnetizing flux current (excitation current) in the transformer core. The study recommends that the generator voltage must be built up at generator speed compatible with the network as close as possible to the network running frequency to reduce the effect of increased magnetic flux (over excitation) during generator start up, which is harmful to the generator, the main transformer, and the auxiliary transformer as much as possible, as well as creating two generator field circuit breakers connected in series.

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