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PERFORMANCE OF AN OVER VOLTAGE RELAY AT HARMONIC POLLUTED CONDITIONS

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Abstract- Power systems have been facing power quality problems due to the penetration of harmonics into the transmission systems caused by increasing nonlinear loads. This paper presents a thorough analysis on the false operation of a reactor installed at the 20 kV side of a 230/63/20 kV transformer. Several measurements are performed at different locations in the area, and power quality indices have been extracted and compared with IEEE 519 Standards. The study shows that the malfunctioning of the reactor is due to the effect of harmonics on the overvoltage relay exciting the reactor. The relation between the harmonic voltage and over voltage behavior is tested in the laboratory. The effect of harmonics amplitude and phase angle on the relay operation is also investigated.

Keywords: Power Quality, Protection Relay, Voltage Relay, Voltage Harmonics, Over Voltage.

I. INTRODUCTION

A broad Protection relay is a device, which controls the operation of a circuit breaker by means of measuring power system quantities (currents and voltages) and processing them through its internal logic. The internal logic allows the relay to initiate a tripping sequence when anomalous conditions arise within the power system. Protection relays typically consist of one or more of the following basic protective components: voltage units (i.e. under voltage and over voltage), over current units, distance protection and differential protection.

Under voltage, over voltage (OV) and over current units are designed to operate when the amplitude of the input quantities exceeds (or falls below in case of under voltage) a preset threshold. The operation can be instantaneous or time delayed. In the last two decades, the number of nonlinear loads is increasing in industry. This increase has in turn, resulted in harmonic pollution in distribution and transmission networks. Harmonics can affect the operation of sensitive electronic equipment as protective relays.

Due to increase of these distortions, the reliability of protection devices may be sacrificed. The influence of distorted waveforms on protective relays is not well documented because of the large variety of measuring principles employed in different relays. The relay can make incorrect operations such as failure or false tripping. The reasons of incorrect operation may be personnel error, incorrect settings, equipment malfunction, poor application or undesired system parameters (harmonic current and voltage).

The power quality disturbances and its effects on protective relay operations are described in [1]. The effects of non-sinusoidal voltages and currents on the performance of under frequency and over current relays were experimentally studied by Fuller et al. [2], and also Tung et al [3]. It was found that for harmonic voltage and current amplitudes, under frequency relays and the time delay operation of over current relays show a marked deterioration in their performance, however, the instantaneous operating characteristics of over current relays are hardly affected.

Girgis, et al. [4] studied the effects of voltage and current harmonics on the operation of four types of solid-state relays. Their experimental results indicate that voltage harmonic distortion may cause a delay in the turn-on time of more than a cycle. In some cases, complete failure of turn on or off may occur. Ref. [5] addresses the effect of harmonics on the operation of a directional distance (OHM unit) relay. Their experimental results show that the relay may report a wrong fault location in the presence of harmonic distortion.

The relay is frequency sensitive for frequency up to 20 kHz, the highest testing frequency, and it is phase sensitive when voltage and current are distorted. A number of relays were tested and each relay responded differently to harmonic distortions. Elmore, et al. [6] describe the theoretical expectations of harmonic influence and present laboratory confirmation for their findings. The results indicate that the influence of mixed frequency harmonics (with magnitude decreasing with order) on the steady state behavior of the protective relays studied is minor and insignificant, however, a distinct change in relay operation is reported for single harmonic injections. The goal of this paper is to study the malfunctioning of an OV relay in a 230/63/20 kV substation, located in North West of Iran.

The logic and philosophy operation of the OV relay is to protect equipment against high voltages. In this substation, to control the OV condition reactors are switched on by the OV relay. The untimely operation of the OV relay will damage the network equipment. To obtain how the solid state based OV relay responds to distorted voltages, this paper summarizes the results of two approaches under non-sinusoidal voltages. The first approach is based on the relay characteristics provided by the manufacturer to investigate the performance of the OV relay, under pure sine waveform.

The second approach is the experimental analysis performed with harmonic rich waveforms. Experimental analysis of this paper indicates that the waveform distortion of system voltage will alter the fail to operate of the OV relay. The structure of this paper is as follows. In sections II and III, the effect of power quality on the protection relay is described. The problem definition and some possible reasons are described in section IV. The simple structure of the overvoltage relay at Moghan substation is described in part V. The harmonic test results of the relay are given in part VI.

II. NONLINEAR MOTOR DYNAMICS

Protective relays play no role when the operation of power systems is stable and normal. They are designed to operate when there are faults involved in the systems. The direct consequence of relay operation is system component cutoff, which definitely affect the operation of the system. Therefore, either fail-to-trip or a mal-trip can lead to considerable economic losses. In the former case, a fail-to-trip makes the fault-involved components remain at critical conditions too long, damaging the components either in short-term or in long-term.

In the latter case, a mal-trip cuts off components that are under healthy operation, possibly causing direct economic losses to customers. Therefore, two characteristics are important for protective relays: sensibility (or dependability in a more formal way) when there is a fault, and immunity (or security in a more formal way) when there is anything other than faults. The former tells how reliable a relay is when it should operate, while the latter tells how robust a relay is when it should not operate. In this sense, protective relays should not react to any power system disturbances. However, most protective relays are designed to deal with the situations when the voltage and current signals are steady-state sinusoidal waveforms.

In case of power system disturbances, whether protective relays will experience a mal-trip is dependent on the type of the disturbance as well as the structure of the relay. To study the impact of power system disturbances on protective relays, it is necessary to apply some typical disturbances during the protective relay testing. The applied disturbances can be either obtained from practical measurements or from reasonable simulation of practical power system structures and events. When we analyze the effect of wave quality on the performance of relays, it is necessary to distinguish the following two types of effect.

It is important to bear in mind that not all power quality related events leading to protection system operation are erroneous. Some protection relays by their design are designed to operate under certain anomalous conditions involving poor quality of power. An example of such operation is an under voltage relay which can initiate a tripping sequence during voltage sags or short interruptions. Long voltage imbalances can also make protection units trip. In such cases, although tripping is caused or influenced by power quality related phenomenon, it is still a legitimate protection system operation.

In summary, it can be said that this type of distortion affects the relay performance, but does not cause incorrect operation. Some power quality related phenomena cause incorrect protection system operations. This is because poor power quality conditions cause the relay to register erroneous input values, and for that reason, it acts erroneously. The opposite situation is also possible when the relay does not trip when it should, due to the poor power quality. The phenomenon that may make a relay work incorrectly is harmonic distortion.

High levels of harmonic in extreme cases can cause relay maloperation, which is mainly a consequence of measurement error of the peak value and/or the angle of the waveform. For that reason, when measuring currents and voltages, the relays should measure the fundamental component of the signal alone.

III. RMS AND THD OF THE NON-SINUSOIDAL VOLTAGE

It is very important imperative to size the overvoltage relay to the true RMS as measured by a true RMS meter. Average sensing, RMS equivalent meters do not correctly respond to harmonic voltages. Harmonic-rich voltage will have higher effective RMS as compared to non-distorted sinusoidal waveforms. The RMS value of a pure sinusoidal waveform ($V_{\text{rms}} = V_{1\text{-rms}}$) is defined as:

$$\begin{cases} v(t) = V_m \sin(\omega t) \\ V_{1-rms} = \sqrt{\dfrac{1}{2\pi}\displaystyle\int_0^{2\pi} v^2(t)dt} = \sqrt{\dfrac{V_{1-\max}^2}{2}} \end{cases} \tag{1}$$

The RMS value of a non-sinusoidal voltage waveform ($V_{ns\text{-rms}}$) is defined as:

$$V_n(t) = V_{1-\max}\sin(\omega t+\phi_1) + V_{2-\max}\sin(2\omega t+\phi_2) + \\ +\ldots+V_{n-\max}\sin(n\omega t+\phi_n)$$

$$V_{n-rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} v_n^2(t)dt} = \tag{2}$$

$$= \sqrt{\frac{1}{2\pi}\int_0^{2\pi}\begin{bmatrix} V_{1-\max}\sin(\omega t+\phi_1)+ \\ \ldots+V_{n-\max}\sin(n\omega t+\phi_n)\end{bmatrix}^2 dt} =$$

$$= \sqrt{\frac{V_{1-\max}^2}{2} + \frac{V_{2-\max}^2}{2} + \ldots + \frac{V_{n-\max}^2}{2}}$$

Simplifying the above equation results in:

$$V_{n-rms} = \sqrt{V_{1-rms}^2 + V_{2-rms}^2 + \ldots + V_{n-rms}^2} \tag{3}$$

The total harmonic distortion is defined as:

$$THD_V = \frac{V_h}{V_{1-rms}} \times 100 \quad (4)$$

$$V_h = \sqrt{V_{2-rms}^2 + V_{3-rms}^2 + \ldots + V_{n-rms}^2} \quad (5)$$

IV. PROBLEM DEFINITION AND EXPERIMENTAL RESULTS

According to malfunction reports of the OV relay in a 230/63/20 kV substation at North West of Iran, the investigations was started. The single line diagram of this substation is shown in Figure 1. As it can be seen, this substation has two parallel 230/63/20 kV transformers fed by a 230 kV line. Due to the structure of the power network in this area and the possibility of over voltages at the 230 kV bus of the power station, a 16.5 MVar reactor is connected in tertiary winding of T1 and T2 at 20 kV voltage level.

The OV relay operation is based on phase-phase voltage measurement at 230 kV side of the substation. When the measured voltage exceeds the set value of the relay (1.1 pu, where voltage base is 230 kV), it switches on the 16.5 MVar reactors to control the over voltage. Based on this substation reports, between 2010 and 2012 almost 20 maloperation of the OV relay were seen. Sometimes, the 16.5 MVar reactors come into the system without any over voltage of the 230 KV bus. In addition, it is reported that, sometimes, there was OV of the 230 kV bus without any operation of the reactor.

This paper explains the steps that have been taken to thoroughly analyze of this problem and it is solving procedure. Two reasons may be considered for the malfunction of the OV relay in substation as follows:
Assumption 1- The malfunction of the relay is due to the voltage harmonics.
Assumption 2- The input to the OV relay from the Capacitive Voltage Transformer (CVT) is not correct.

To investigate the possibility of these assumptions, three-phase voltages at 16 points have been measured for three weeks including Moghan substation. Measuring Center (MC) shows the measurement points in Figure 1. This figure shows that MCs are in 230 kV, 63 kV and 20 kV voltage levels. The measurements have been done using Hioki-3196 power quality analyzers. The following results have been obtained through measurement analysis.
1- The RMS voltage at the 230 kV bus in substation is almost equal to the measured values at other substations in the area Therefore, assumption (2) could not be correct.
2- The RMS voltage at the 230 kV (V_n) bus in the substation never reaches the trip threshold of the OV relay.
To investigate the operation of the OV relay the following settings are examined during the test period and records of their operations:
a- 110% V_n with 5 sec delay, with this setting, the relay never operated, and the reactors never came into network.
b- 110% V_n with 3 sec delay, with this setting, the OV relay operated only once and the reactor was called in.
c- 105% V_n with 3 sec delay, in this case, the OV relay operated several times, and caused the operation of the reactor as well.

Figure 2 shows 3-phase voltage measurements results at the 230 kV bus at Moghan substation when the OV relay operated. In this figure, at 2:41 after the OV relay operated the reactors switched on and resulted in a voltage decrease to an unwanted value and At 2:42 the operator of the substation had to switch off the reactor manually.

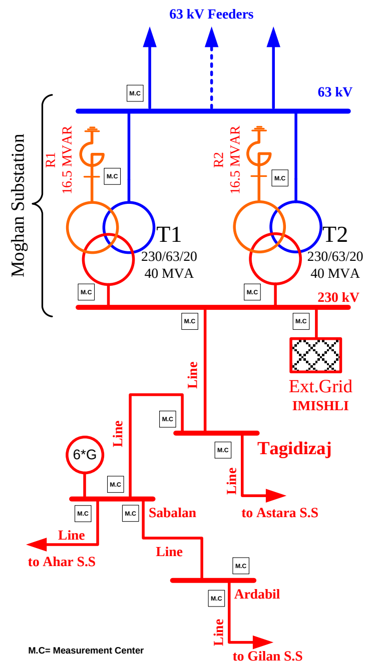

Figure 1. Single line diagram of Moghan substation

It can be seen that the RMS voltage has decreased due to the insertion of the reactor. However, as it can be seen, the RMS voltage has never reached the relay trip threshold, i.e., 230 kV ± 10%. Therefore, one can conclude the following:
1- The input to the relay from the CVT is correct.
2- The results of Figure 2 (between 2:40:00 to 2:41:00) prove that the operation of the OV relay is not due to the increase in the RMS voltage.

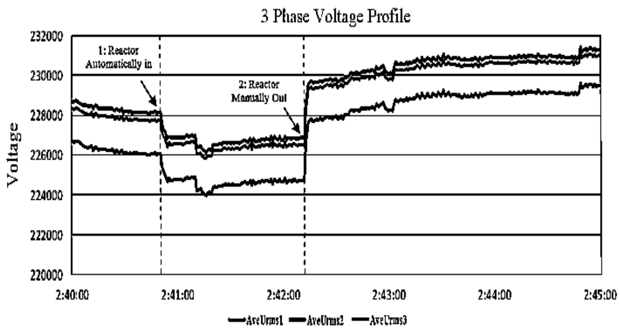

Figure 2. Voltage of 230 kV bus-bar power station while reactor is connecting

Measurements results show that the dominant harmonic on the 230 kV bus is the 5th one and other harmonics can be neglected. Based on Figure 3, the 5th harmonic magnitude at the 230 kV side of Moghan substation is less than 12%.

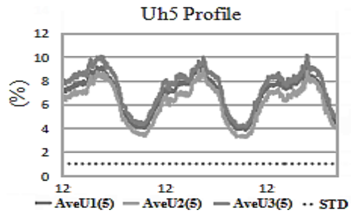

Figure 3. Depicts the 5th harmonic in substation at the 230 kV bus

As Figure 3 shows, although the magnitude of the 5th harmonic voltage is much higher than the IEEE 519 Std. limits, it cannot result in considerable increase in the RMS voltage. A 12% harmonic can increase the RMS by only 0.72%. This study also proves that the relay is being affected by parameters other than the RMS value. Therefore, it is needed to check the relay structure and find its principle of operation.

V. OVER VOLTAGE RELAY STRUCTURE

The OV protection used in Moghan substation is a solid-state OV relay of type VTU manufactured by GEC protection & control Ltd Company [8]. Figures 4 and 5 show a photo and a block diagram of this relay. The first block of the relay is a step-down transformer to bring the CVT output voltage down to the level of the relay static structure. A surge arrester is put in parallel with the input transformer to divert high voltage spikes and protect relay.

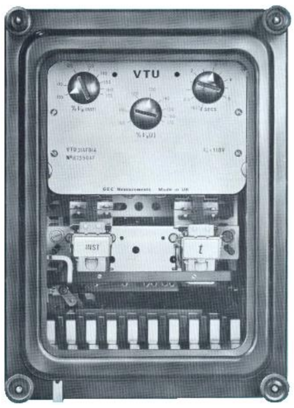

Figure 4. Photo of OV relay

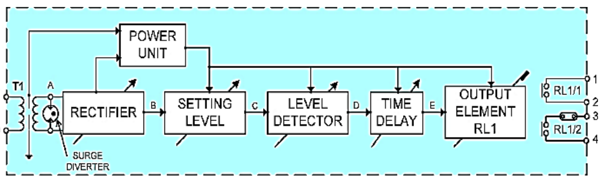

Figure 5. Block diagram of VTU relay

The output of transformer is an input to a full-bridge rectifier, which feeds a resistance and a zener diode. The zener output is an input to a level detector. The level detector output will be then compared with a threshold limit. The comparator output is then passed through a programmable delay, which can excite the relay output contacts. The structure of the relay, which is of a static type one, shows that the relay detects the peak of the input signal, and therefore, can be sensitive to harmonic angles.

To further examine the harmonic effects, the relay is taken to a power quality lab and tested using an AC power supply. This AC power supply is able to generate harmonics at a designed frequency and amplitude. Figure 6 and Figure 7 show the output waveform of the inner transformer and rectifier of the VTU relay respectively (points "A" and "B" in Figure 4). Figure 8 and Figure 9 show the relay input with 20% - 5th harmonic with 0° and 180° phase shift respectively.

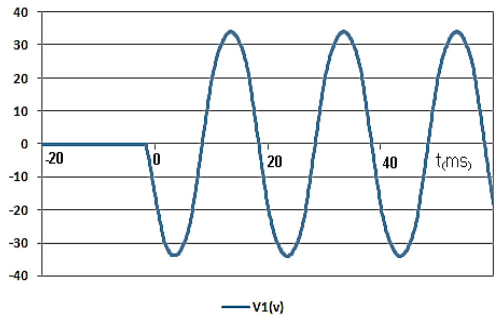

Figure 6. Output waveform of the internal transformer of the VTU relay (Point A)

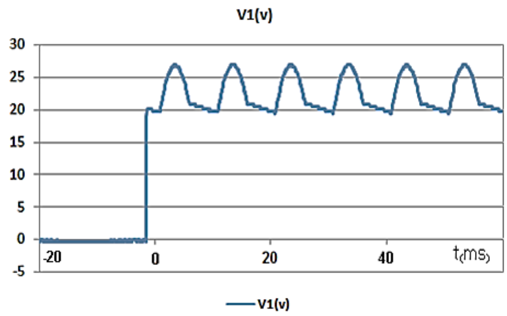

Figure 7. Output waveform of the rectifier (Point B)

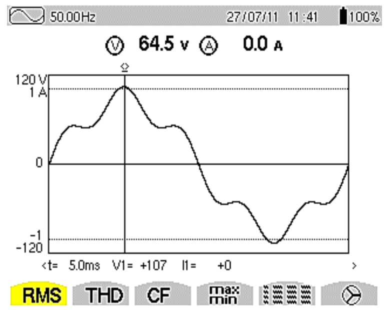

Figure 8. Voltage waveforms with the fifth harmonic in phase with the fundamental voltage

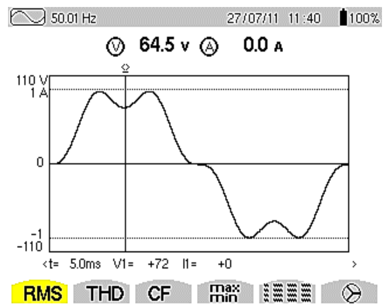

Figure 9. Voltage waveforms with the fifth harmonic with 180° phase displacement with the fundamental voltage

Table 1. Experimental test results

Number of test	Magnitude of fundamental voltage (kV)	Magnitude of 5th harmonic of voltage (%)	Phase angle of 5th harmonic of voltage (degree)	RMS voltage increment (%)	Trip threshold of OV relay (%)	Delay of OV relay (Sec)	Operation of VTU	Operation of PL70
1	63.4	0	0	0	5	0.5	No	No
2	64.8	0	0	2.2	5	0.5	No	No
3	65.9	0	0	3.9	5	0.5	No	No
4	66.5	0	0	4.88	5	0.5	No	No
5	67.1	0	0	5.8	5	0.5	Yes	Yes
6	67.1	0	0	5.8	5	3	Yes	Yes
7	66.9	0	0	5.5	5	3	Yes	Yes
8	66.6	0	0	5.04	5	3	No	No
9	63.4	20	0	1.73	5	3	Yes	No
10	63.4	14.8	0	0.95	5	3	Yes	No
11	63.4	12.5	0	0.63	5	3	Yes	No
12	63.4	10	0	0.3	5	3	No	No
13	63.4	9.8	0	0.32	5	3	No	No
14	63.4	9.8	0	0.32	Max	3	No	No
15	63.4	20	180	1.73	5	3	No	No
16	63.4	12.5	180	0.63	5	3	No	No
17	63.4	12.5	100	0.63	5	3	No	No
18	63.4	12.5	10	0.63	5	3	Yes	No
19	63.4	12.5	40	0.63	5	3	Yes	No
20	69.7	0	0	9.9	10	3	No	No
21	71.8	0	0	13.2	10	3	Yes	Yes
22	71	0	0	11.8	10	3	Yes	Yes
23	71	10	0	11.8	10	3	Yes	No
24	71	10	180	11.8	10	3	Yes	No
25	71	10	140	11.8	10	3	No	No
26	69	20	0	11.9	10	3	-	No
27	69	40	0	17	10	3	-	No
28	69	60	0	26.6	10	3	-	No

It can be seen from these figures that although the two waveforms have the same harmonic amplitudes, they show different peak values. With this observation, the following scenarios may occur.

1- A 5th harmonic which is in-phase with the main signal can considerably increase the signal peak value (e.g. equal to the % of the harmonic), and therefore, it may result in a relay operation without a considerable increase in the signal total RMS value.

2- A 5th harmonic which is 180° out of phase with the main signal, can considerably decrease the signal peak value (e.g. equal to the % of the harmonic), and therefore, may prevent the OV relay from operation even if the main signal RMS value is higher than the relay threshold limit.

VI. HARMONIC TESTS

To further study the effects of harmonic angles on the OV relay, several tests have been performed. Table 1 summarizes the test results. Based on the harmonic tests, the following results have been obtained.

1- The VTU OV relay operate according to its settings in sinusoidal environments.

2- With 20% in-phase 5th harmonic, the relay operates, although the RMS value has not changed considerably.

3- With 20% out-of-phase 5th harmonic, the relay does not operate.

After these observations, another test was performed at Moghan substation. A digital relay of PL70 type (Ingeteam) is used in parallel with the VTU, OV relay. Several maneuvers have been performed in the network. The results show mal-operation of the VTU OV relay again due to the harmonics, but the PL70 relay does not. The PL70 relay is a fundamental RMS type relay meaning that it responds only to the RMS value of the fundamental signal [9]. In the input block of this relay, a filter is used to extract the input fundamental value.

VII. CONCLUSIONS

This paper thoroughly investigates the malfunction of an OV relay in a 230 kV substation. The study shows that this type of relay is very sensitive to the phase angle of harmonics. Since this relay works based on the peak value of the input signal, harmonic can significantly affect its operation. Therefore, it is recommended that in harmonic environments relays, which are not sensitive to harmonics, are used. Also the results of this paper shows that the operation of the OV relay by GEC in harmonic polluted condition should be studied carefully and if it is necessary, the relay should be replaced with ones which are insensitive to harmonics.

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BIOGRAPHIES

Babak Asadzadeh was born in Sardasht, Iran in 1975. He received the B.Sc. degree in Electrical Engineering from the University of PWUT, Tehran, Iran, in 1998 and the M.Sc. degree from University of Tabriz, Tabriz, Iran, in 2008. His current research interests include modeling and application of power electronic devices in power systems. He is employee in Azerbaijan Regional Electric Company, Tabriz, Iran as head of power quality and DCS system group.

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Hossein Mokhtari was born in Tehran, Iran, on August 19, 1966. He received his B.Sc. degree in Electrical Engineering from Tehran University, Tehran, Iran, in 1989. From 1989-1992, he worked in the Consulting Division of Power Systems Dispatching Projects for the Electric Power Research Center Institute. He obtained his M.Sc. degree in Power Electronics from the University of New Brunswick, Fredericton, NB, Canada, in 1994, and his Ph.D. degree in Power Electronics / Power Quality from the University of Toronto, Toronto, ON, Canada in 1999. Since 2000, he has been with the Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran. He is currently a Professor in this department. He is also a senior consultant to several utilities and industries. His research interests include power quality, power electronics and its application in power distribution systems, micro-grids, wide area measurements and smart grids.

Mehrdad Tarafdar Hagh received his B.Sc. and M.Sc. degrees both with first honor in 1988 and 1992, respectively and Ph.D. degree in 2000, all in Power Engineering from University of Tabriz (Tabriz, Iran). He has been with the Faculty of Electrical and Computer Engineering, University of Tabriz since 2000, where he is currently a Professor. He has published more than 150 papers in power system and power electronics related topics. His interest topics include power system operation, FACTS and power quality.