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Differential Protection Strategies for Synchronous Motor :A Case Study

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Abstract: **Three-phase synchronous motors are widely used in the industrial motor driven systems. Variable frequency drives (VFDs) which allow soft-start of motors produce PWM voltage. Numerical relays are used in the protection schemes of these high voltage motors. The location of current transformer (CT) is an important criterion in the protection circuit. Impact of harmonics and the location of current transformer in the motor starting circuit is analysed considering a case study. A suitable protection strategy recommended by IEEE for synchronous motor driven by VFD is presented.**

I. INTRODUCTION

Variable frequency drives are used for starting and controlling the speed in case of induction motors and only for starting (to limit the starting current) in case of synchronous motors. With rapid developments in electronics, solid state devices have become very popular in electric drives. Harmonics produced by line-commutated converters are related to the pulse-number of the device [1]. The converters are classified according to the pulse number and increasing the pulse number greatly improves the performance of the converter. The inverters used in VFD are classified according to the type of voltage control. In the case of inverters with constant link voltage, the principle of (pulse width modulation) PWM is used. Current harmonics in the VFD input stage can also feed back into the power bus grid, and can disrupt other types of equipment in the premises [2]. The motor has to be protected against any abnormal operating conditions like overcurrents, overvoltages, short-circuits etc. Current transformers in co-ordination with numerical relays are used for the protection. But the choice of the location of the current transformer plays a crucial role in the protection strategy. An inappropriate location of the CT can cause mal-operation of the protection equipment. After a thorough study of the drive system, certain protection strategies for the synchronous motor are recommended.

II. INVERTERS FOR VFD

The VFDs are classified in the form of the variable-voltage/variable frequency power that is supplied to the motor [3]. They are classified as: Variable-Voltage Inverter is also known as a voltage-source inverter (VSI) and a six-step voltage inverter. In this class of VFD's, the controlled variable is the voltage of the motor. The current is determined by the motor's impedance. Current-Source Inverter (CSI) is also known as a six-step current inverter. In this class of VFD's, the controlled variable is the current to the motor. The voltage is determined by the motor's impedance. Pulse width Modulated (PWM) Inverter does not change the amplitude of the controlled variable to the motor (typically voltage). They change the rms value by turning the controlled value ON and OFF at a relatively high frequency while varying the pulse width.

III. BASIC OPERATIONAL FEATURES OF VFD AS SOFT-STARTER

Introduction of a VFD allows "soft starting" and constant speed adjustments according to load requirements. The process therefore can be more closely monitored and controlled, with tremendous energy savings as well as performance improvement. [4]. In VFD applications, the starting currents are minimized. The soft start technology constantly monitors the voltage and current going to the motor. When the voltage and current sine waves diverge greatly or when the motor is lightly loaded and operating inefficiently, the soft start reduces the current and voltage appropriately, while always maintaining the motor at a constant (full) operating speed. When the load on the motor increases, the soft start reads this condition and increases the power to the motor so that it does not stall. A Soft Start keeps the motor running at full RPM.

IV. EFFECTS OF HARMONICS ON PROTECTION EQUIPMENT

Due to extensive application of nonlinear loads like VFDs the load current usually contains harmonic components that affect the operating characteristic of the overcurrent relay [5]. Current with a high crest factor can also nuisance-trip peak sensing devices. The current waveform distortions contain low order harmonics with different THD levels. The waveform distortion of load current will alter tripping time of overcurrent relays. Harmonic-rich currents will have higher effective rms value as compared to non-distorted sinusoidal waveforms. The total harmonic distortion of load current is defined as:

$\%THD_1=(I_h/I_{1rms})*100$,where $I_h=\sqrt{}(I_{2rms}{}^2+ I_{2rms}{}^2 + I_{2rms}{}^2 +..........+I_{2rms}{}^2)$

Waveform distortion does affect the performance of protective relays and may cause them to operate improperly. However, for overloaded conditions (or for low magnitude faults) the current may contain substantial harmonics and distortion can become a significant factor. The effect of harmonic currents leads to a shortened operation time of the solid-state relays. The relay performance depends on THDI waveform distortion. The higher the THD1, the greater is the variation in tripping time. As the magnitude of the fundamental current increases the relative impact of harmonic current on relay tripping is reduced.

The voltage or current spikes fed back in to the distribution system create a high current crest factor and so the peak to RMS current ratio is higher than 1.414. Current having a high crest factor can also cause inaccurate secondary current in transformers. High current peaks may lead to transformer saturation. When the saturated secondary current is fed through a resistance, the resulting voltage wave wil1 have suppressed or flattened peaks. The current transformation under saturated conditions is therefore nonlinear.

True RMS sensing devices are required to provide reliable overcurrent protection when harmonics are present [6]. Size the overcurrent devices by measuring 1oad current using only true RMS sensing meters.

It is impossible to generalize the behaviour of any relay response to harmonics without actual tests, as the actual test results show larger deviations than that of theoretical calculation and software simulation.

Relays exhibit a tendency to operate slower and/or with higher pickup values rather than to operate faster and/or with lower pickup values [7]. The overvoltage and over-current relays exhibit various changes in the operating characteristics. Depending on harmonic content, the operating torque of the relays could be reversed. The harmonic currents add to the normal line currents, which is why the input current to a VFD is higher than the output current (by approximately 30%). Hence, there is distortion in the current seen by the CT. This differential current is more which may cause mal-operation of the relay. To decrease the harmonic content, a 12-pulse converter is employed. For the twelve-pulse system, the input current will have theoretical harmonic components at the following multiples of the fundamental frequency are 11, 13, 23, 25, 35, 37, etc. The 5th and 7th harmonics are absent in the twelve-pulse system. The problem with 12-pulse configuration is that the two rectifiers must share current exactly to achieve the theoretical reduction in harmonics. This requires a converter transformer.

V. VFD SOFT START SYNCHRONOUS MOTOR CONFIGURATION IN INDUSTRY-A CASE STUDY

A VFD is the ideal soft starter since it provides the lowest inrush of any starter type reduces thermal and mechanical stresses on motors and belts [8]. Any power converter that converts ac to dc or dc to ac can be considered to be a source of harmonics [9].

A case study will be considered to show the area of application. An 8350 KW, 16 poles, 375 RPM Salient Pole Synchronous motor is fed by 6.6 KV bus driving Hydrogen compressor unit. The system configuration is as shown in figure 4. The motor at starting is driven by a soft starter which is a Converter-Inverter configuration used to supply a dc field excitation and stator of synchronous motor. Once the motor reaches to its rated speed it is then brought to a 6.6 KV bus. The currents measured during the start at different levels are seen in the single line diagram as shown in figure 4. The motor is provided with differential protection with CT-2 and differential protection relay element 87.

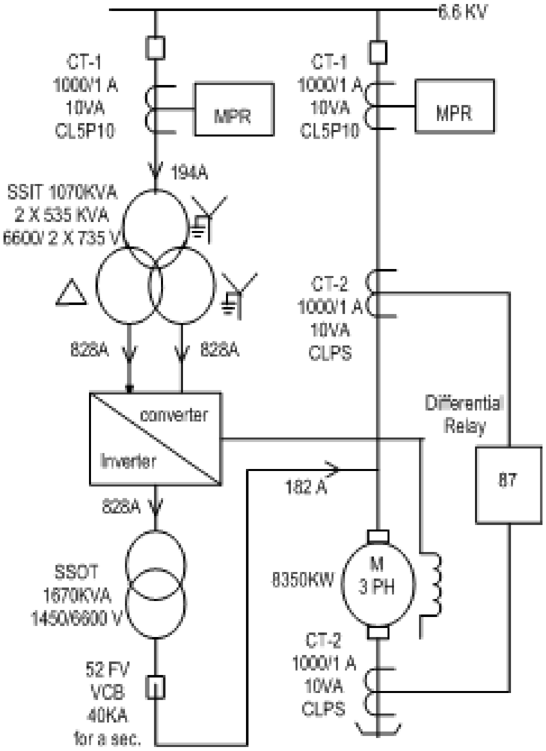

Fig.4 Single Line Diagram: Case Study

During starting operation the motor is fed through 1070KVA, 6600/2 x 735V converter transformer and 12 pulse soft starters. The converter transformer is built with two valve windings of equal power and voltage ratings. One of the windings is connected in star and the other in delta. Soft starter is a converter inverter configuration which supplies controlled dc and ac power to field excitation and 3 phase stator of the motor. From the inverter, power is supplied to the stator of motor through 1670 KVA, 1450/6600 V step down transformer. With this configuration, there are mainly two technical issues which have been analyzed.

A. *Difference in current supplied to motor and current taken by motor.*

The measured current at the input of stator of synchronous motor is = 182 A

The current at the primary of converter transformer is = 194A

From these measured values we can say that harmonic current is getting injected into the source side. And these harmonics are produced due to the converter inverter configuration and the converter transformer. So, the harmonic analysis has been carried out to show how this difference in current has been generated.

Harmonic Analysis:

The RMS values of harmonic components are inversely proportional to their harmonic order

$$I_{SH} = \frac{I_{S1}}{h}$$

Where, I_{S1} = RMS value of fundamental frequency current

$h = 12n \pm 1$

For the twelve-pulse soft starter input current will have theoretical harmonic components at the 11, 13, 23, 25, 35, 37, etc. multiples of the fundamental frequency. So, contributions of different harmonic currents due to 12 pulse soft starter are:

$$I_{SH11} = \frac{I_{S1}}{h} = \frac{182}{11} = 16.54 \text{ A}$$

$$I_{SH13} = \frac{I_{S1}}{h} = \frac{182}{13} = 14 \text{ A}$$

$$I_{SH23} = \frac{I_{S1}}{h} = \frac{182}{23} = 7.91 \text{ A}$$

$$I_{SH25} = \frac{I_{S1}}{h} = \frac{182}{25} = 7.28 \text{ A}$$

$$I_{SH35} = \frac{I_{S1}}{h} = \frac{182}{35} = 5.2 \text{ A}$$

$$I_{SH37} = \frac{I_{S1}}{h} = \frac{182}{37} = 4.91 \text{ A}$$

The Effective value I_H of all the harmonics produced by 12 pulse soft starter is given by the equation:

$$I_H = \sqrt{I_{SH11}^2 + I_{SH13}^2 + I_{SH23}^2 + I_{SH25}^2 + I_{SH35}^2 + I_{SH37}^2}$$

The effective value of distorted current is given by the equation

$$I = \sqrt{I_F^2 + I_H^2}$$

Where,

I = Effective value of distorted current

I_F = Effective value of fundamental current

I_H = Effective value of all the harmonics produced by soft starter

$$I = \sqrt{I_F^2 + I_{SH11}^2 + I_{SH13}^2 + I_{SH23}^2 + I_{SH25}^2 + I_{SH35}^2 + I_{SH37}^2}$$

The effective value of the distorted current is:

$$I = \sqrt{182^2 + 16.54^2 + 14^2 + 7.91^2 + 7.28^2 + 5.2^2 + 4.91^2}$$

$$= \sqrt{33760.28}$$

$$= 183.73 \text{ A}$$

Harmonics generated due to Star- Delta connection of transformer: In star delta connection the magnetic flux linking both the primary and secondary winding is a sine wave. As a result of this, the primary and secondary phase emfs are free of third harmonic emfs and their waveforms are almost sine waves. So, no harmonics generated due to star delta connection of transformer. Harmonics generated due to Star- Star connection with neutral of transformer: If, alternator and the primary of star-star connected transformer have their neutral grounded, then third harmonic current can return through the ground. Therefore third harmonic magnetizing current can exist in the lines and in the phase windings of the transformer [7]. So, a contribution of 3rd harmonic currents due to star- star connection of transformer is:

$$I_{S3} = \frac{183.73}{3} = 61.2 \text{ A}$$

So, Total current distortion at source end is

$$= \sqrt{183.73^2 + 61.2^2}$$

$$= 193.6 \text{ A}$$

$$\cong 194 \text{ A}$$

So the harmonic current injected by soft starter and converter transformer gives rise to the increase in current towards source side [5]. The current obtained with harmonic analysis is same as the measured current.

B. *Location of CTs for differential protection of motor.*

In the given system, the differential protection is provided for the motor with the relay element 87. The differential CTs are connected as shown in figure 4.In this configuration, one CT-2 is located before the soft-starter and the second CT-2 is located at the input of the motor. With this way of connection of CT if the motor is started, unequal current flows through the two differential protection CTs i.e. CT-2. Harmonic currents add to the normal line currents, which is why the input current to a

VFD is higher than the output current. This difference in current flowing through differential relay element 87 causes it to operate and give tripping signal to circuit breaker. So, the given location of CT is not recommended.

VI. RECOMMENDED PROTECTION STRATEGIES FOR SYNCHRONOUS MOTOR:

A. Recommendation-1

Differential protection CTs should be connected across the stator winding to avoid the harmonic currents flowing through the CTs and to prevent the mal-operation of the protection equipment. as shown in figure 5.

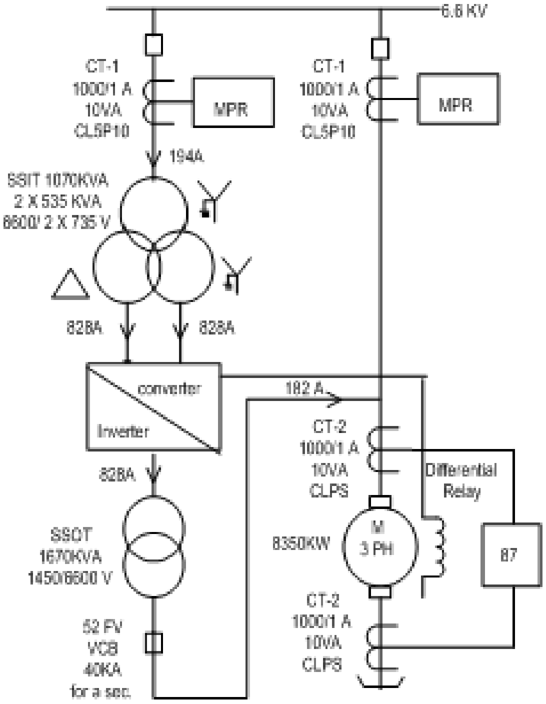

Fig.5. Recommended CT Location

B. Recommendation-2

For high power rated Synchronous motors, differential protection as recommended by IEEE can be provided using flux balance CTs. This protection strategy uses three current transformers, one per phase (Self Balancing Differential Protection). This provides the ability to monitor each phase of an incoming line and thereby alert the user to any conditions of unequal current, either in the power source or in the motor windings. It can be set to detect faults as low as 5% to 10% amps primary current. This recommended connection is as shown in figure 6.

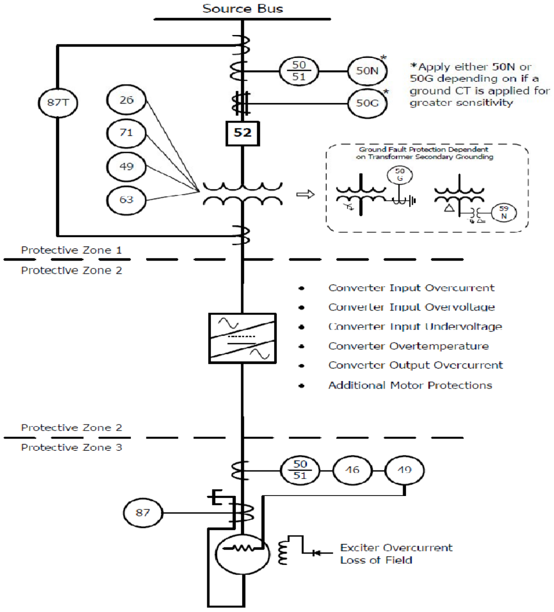

Fig.6. Recommended protection for Synchronous motor

VII. Conclusion

A careful design and selection of VFD decides the harmonic distortion of the drive system. The harmonics generated by the VFD can cause maloperation of the protection equipment. Harmonic currents add to the normal line currents, which is why the input current to a VFD is higher than the output current. Considering the effects caused by harmonics the motor should be protected. As a part of the protection strategy, a suitable location of the current transformer should be selected in the motor protection circuit. The self-balancing differential scheme of protection for the synchronous motor driven by VFD is recommended.

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