Abstract— In this paper an effective direct torque control (DTC) for a 5-phase induction motor with sinusoidal distributed windings is developed. First by coordinate transformation, the converter/motor models are represented by two independent equivalent d-q circuit models; and the 5-phase VSI input are decoupled into the torque producing and non-torque producing harmonics sets. Then with the torque production component of the induction motor model, the space vector modulation (SVM) can be applied to the five-phase induction motor DTC control, resulting in considerable torque ripple reduction over the lookup table method. Based on the decoupled system model, the current distortion issue due to lack of back EMF for certain harmonics is analysed. Two equally effective SVM schemes with the harmonic cancellation effect are introduced to solve this problem. To analyse the DTC control torque ripple, an insightful perspective (also applicable to 3-phase analysis) is introduced to predict the torque ripple pattern evolution with changing motor speed and stator flux angular position. Therefore the switching sequence for lowest torque ripple can be determined and rearranged online.

I. INTRODUCTION TO POWER SYSTEM PROTECTION

One of the major and important sources of energy which became almost the part of human life is "Electrical energy". The word "Power system" includes electric power generation, transmission and distribution along with "Protection".

"Power system Protection" includes the protection of the generating, transmitting and distributing equipment from the abnormal conditions (generally called "Faults") developed because of various reasons.

Whenever an abnormal condition or fault has occurred and if it is not cleared within a short duration, the entire power system may collapse. That is if a fault sustains for a long time, all the equipment connected to the power system would be damaged permanently which is mostly undesirable. A protection scheme must take care to avoid these undesirable conditions. This approves the significance of protection in any power system.

As the power system protection is a continuous operation, manual control over this operation is not possible always. So, one should take the help of automation in the case of power system protection. The equipment which is used for "Protection scheme" is generally referred to as "Switchgear". This Switchgear includes Protective Relays, Circuit Breakers, Isolators, Earth switches, lightening arrestors, Fuses, etc. A protection scheme will be planned for every power system which makes the best use of switchgear equipment, primary protection scheme, and secondary or back-up protection scheme.

A. Evolution of relay

In the very early days of power industry, small generators were used to supply local loads and fuses were the only devices to isolate the faulty equipment. Although they were efficient, they suffer from replacement problem. This inconvenience was overcome with introduction of Circuit Breakers and electromagnetic Relays.

With the tremendous expansion of interconnected power systems, there has been a demand for more reliable and advanced systems of protection which led to the development of solid state or static protective relays, eliminating all moving parts. In the early 1920's attracted armature type, induction disc type electromagnetic relays were introduced. They were used for over current protection.

In 1939 induction cup type of relays were introduced and they were used for directional and distance protection.

In 1940's static relay using vacuum tubes for transmission line protection were introduced. But they are not accepted because of complexity and shorter life of vacuum tubes. In 1947 Rectifier Bridge type comparators were developed in Norway and Germany. Soon after innovation of transistor, first transistorized relay was produced in 1949. During 1965-75 digital static relays, digital computer based relays were developed for transmission systems.

During 1975-85, microprocessors are introduced into protection schemes. In the period of 1985-95 combine (integrated) protection, control and monitoring systems based on digital computer and microprocessor were developed and after that supervisory control and data acquisition systems (SCADA) and energy management systems (EMS) were introduced.

II. PROBLEM DEFINITION

Designing of a static impedance relay by using the integrating type and phase splitting type of the coincidence type phase comparator.

A. Introduction to Distance protection schemes

This scheme employs a number of distance relays which measure the impedance or some components of line impedance at the relay location. The measured quantity is proportional to the line length between the location of the relay and the point where the fault has occurred and the relay will operate, i.e. Issues trip signal, if the measured quantity is less than the reference quantity. As the measured quantity is proportional to the distance along the line, this relay is called a Distance relay. Distance protection is widely used for the protection of Extra High Voltage (EHV) transmission and sub-transmission lines. These relays provide high speed fault clearance.

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Kalyan Aravalli

1Department of Electrical and Electronics SRM University, Chennai
Most important and versatile family of distance relays includes following types:
1. Impedance relay.
2. Reactance relay.
3. Mho relay

B. Types of phase comparators
A comparator which compares two input signals in their phase is referred as phase comparator. According to the principle there are two types of phase comparators:
1. Vector product phase comparator
2. Coincidence phase comparator

C. Vector product phase comparator
In these comparators, the output is proportional to the vector product of AC input signals. The Hall Effect phase comparator and magneto-resistivity phase comparator come under this category.

D. Coincidence type phase comparator
In a condense type phase comparator, the period of coincidence of positive polarity of two input signals measured and compared with a predetermined angle, usually 90°.

III. MATLAB PROGRAM:
As discussed in earlier chapters a phase comparator which realizes a static impedance principle is designed with the help of simulink block diagrams. An "Integrating type Coincidence Phase comparator" is realized in our work.

Fig. 1: Block diagram of a main system
The figure 1 gives the connections of simulink blocks which implements a impedance principle and the figure involves a sub-system which is basically the design of integrating type phase comparator. The complete block diagram representation of the sub-system is as shown above.

A. Block Diagram Description
The block diagram depicted in fig 4 performs the phase comparison to realize impedance relay. Fig 4 involves a sub-system which is shown on detail in the fig 6. For the ease of understanding, let us deal with the sub-system first.
1) Sub-system description:
This sub-system is a two input system. Generally, these two inputs are sinusoidal in nature. At first stage, these two inputs are converted into Square waves with the help of Saturation Block. The two inputs, after converting into Square waves, are applied to an "AND" gate. The "AND" gate acts as a coincide detector in which positive polarity coincidence of two waves is identified. The output from the "AND" gate is applied to an integrator, which is having as reset action for every one cycle time. The integrator output is fed to a comparator which compares the integrator output level with a pre-specified constant value. Generally this pre-specified constant will be that level when the two signals are having the exact phase difference of 90°. The comparison will be done in such a fashion that if the input signals phase difference is less than or equal to 90°, an output signal, generally called the "Trip signal" is generated. Otherwise the output signal remains at zero position.

2) Main block diagram description
As discussed in chapter 3, section 3.4.2, the inputs for an integrating type coincidence phase comparator must be (IZr-V), (IZr+V). Where I- current under fault condition V-Voltage under fault condition Zr-impedance value As the sub-system represents the phase comparator, the inputs will be (IZr-V) and (IZr+V). Taking use of CTs, PTs, fault current and voltages can be measured from the faulty lines and are manipulated to get, (IZr-V) and (IZr+V). For this I is multiplied with |Zr| and appended with a phase angle, which is equal to impedance angle, and the V is subtracted from IZr which results in (IZr-V). This signal is given to the one of the inputs of sub-system. Again, I is multiplied with |Zr| and the result is appended with an angle 90° to get IZr. This is directly given to the other input of the sub-system as shown in figure 3.3. For the ease of understanding, one can refer section 3.4.2 and 3.5.1 from chapter 3.
If the phase angle difference between \((IZr-V)\) and \((IZr+V)\) is less than 90°, then the relay will operate, or in the other words, if the fault impedance falls below the reach-value of the impedance, the relay will issue a trip signal. If the phase angle difference between \((IZr-V)\) and \((IZr +V)\) is greater than or equal to 90°, then the relay will not operate, or in the other words, if the fault impedance falls below the reach-value of the impedance, the relay will not issue a trip signal.

IV. MODEL CALCULATION:

For the impedance relay with the integrating type phase comparator, let us consider \(3+j4\) as the impedance corresponding to the reach-impedance \(3+j4\). And now, consider two different cases under fault conditions.

Case (i):

Fault voltage \(V=20+j0\) Fault current \(I=8+j4.5\)

\[
IZr-V = [(8+j4.5) (3+j4)] - [20+j0] = -14+j45.5
\]

From the above calculations, the angle of \((IZr-V)\) is 107.103°

\[
IZr+V = [(8+j4.5) (3+j4)] + (20+j0) = 26+j45.5
\]

From the above calculation, the angle of \((IZr+V)\) is 60.255°. By observing the two angles, the angular difference between the two quantities is found to be 46.847° (figure 4.1(a)), which is less than 90°. So for this kind of fault conditions, relay should operate.

Cross-check:

From the fault voltage and current, we can calculate the fault impedance as

\[
\frac{V}{I} = (1.8991-j 1.06825).
\]

In which the impedance part \((1.8991-j1.06825)\) is less than the reach-impedance value \((3+j4)\). Hence the relay should operate as shown in figure 5. Fig 4 depicts the graphs for case (i) at different stages of phase comparator.

Fig (a) - sinusoidal wave of \((IZr-V)\) is converted into square wave.

Fig (b) - sinusoidal wave of \((IZr+V)\) is converted into square wave.

Fig (c) - AND gate output i.e. coincidence period is shown.

Fig (d) - integrated output.

Fig (e) - TRIP signal output

Case (ii):

Fault voltage \(V=20+j0\);
Fault current \(I=1.75-j3\);

\[
IZr-V = [(1.75-j3) (3+j4)] - [20+j0] = -2.75-j2
\]

From the above calculation, the angle of \((IZr-V)\) is – 143.973°.

Fig 5: Diagram for when relay is not operating

\[
IZr+V = (1.75-j3) (3+j4) = 37.25-j2
\]

From the above calculation, the angle of \((IZr+V)\) is -3.07333°. By observing the two angles, the angular difference between the two quantities is found to be +/-139.893° (fig. 4.2(b)), which is greater than 90°. So for this kind of fault conditions, relay should not operate.

Cross-check:

From the fault voltage and current, we can calculate the fault impedance as

\[
\frac{V}{I} = (2.90155+j4.974).
\]

In which the impedance part \((2.90155+j4.974)\) is greater than the reach-impedance value \((3+j4)\).

Hence the relay should not operate as shown in fig. 5.

Fig (a) - sinusoidal wave of \((IZr-V)\) is converted into square wave.

Fig (b) - sinusoidal wave of \((IZr+V)\) is converted into square wave.

Fig (c) - AND gate output i.e. coincidence period is shown.

Fig (d) - integrated output.

Fig (e) - TRIP signal output

However there are bigger issues and considerations which have influenced the pace of development in static relays, such as following:

1. Better performance and characteristics, e.g. higher speed with greater accuracy and sensitivity in distance relays.
2. Greater standardization in manufacture
3. Easier manufacture and reduction in maintenance time.

On the other hand, the static relays offer numerous advantages such as:

1. Low burden on CTs and PTs, unlike in electromagnetic relays, since in many cases, operating power is supplied from an auxiliary DC supply.
2. Absence of mechanical inertia and bouncing.
Contacts which assures high resistance to shock and vibrations.
3 Very fast operation and long life.
4 Low maintenance owing to the absence of moving parts and bearing friction.
5 Reset operation is so quick.
6 Greater sensitivity is provided because of amplification facility.
7 Most important merit over the electromagnetic relays is the realization of unconventional characteristics.

V. CONCLUSION

The subject of static relays originated about three decades ago. The emergence of transistor and all other solid state devices has given a great boost to the development of solid state relays. And today, many of the power systems are adopting them into their overall protective schemes.

From the work carried out, it can be concluded mainly that the Static relays possess higher amount of accuracy when compared to electromagnetic relays and does not prone to mal operations. From the simulation output wave forms, analysis of the static relays under different fault condition can be done easily. However, static relays possess such great advantages over electromagnetic relays. Still electromagnetic relays are in use because of their greater accessibility. Under advanced development at present are the non-conventional comparators like instantaneous comparators and phase sequence detectors. Currently, there is extensive work going on the application of advanced static relays based on analog and digital computers to the power system protection. So, one can understand that the static relays play an even greater and significant role in the power system protection.

REFERENCES