Numerical Three Stepped Distance Relay

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***Abstract*—This paper describes the design and development of numerical three stepped distance relay for the protection of high voltage line. The characteristic of the relay is generated by the software designed in Visual Basic 6. The software calculates the magnitude of resistance and reactance by using differential equation principle. The analog voltage and the current signal are given to the computer through Advantech device. The software samples the input analog signals and estimates impedance for characteristic development. Trip signal is generated by software according to the compared results.**

***Keywords*—Three Stepped Distance Relay, numerical relay, Protection of Transmission Line, Relay Software , Advantech Device USB4711/A**

I. INTRODUCTION

The impact of modern developments in digital technology has been felt in many areas of Power system protection. The protection of transmission lines is one of the most challenging problems in the area of digital protection of power system. The microprocessor based protection scheme is especially preferred for transmission line since several types of threshold characteristics can be implemented with the same hardware or with a minimum change in hardware. With the advent of the microprocessor, the implementation of this type of protection promises to be cost effective. [1]

Distance relays are the preferred choice for the protection of High Voltage lines. In three stepped distance protection, the relay is set for protection of line in three steps with suitable time delay between each step for back up. In this project to design three stepped distance relay, one quadrilateral relay and two reactance relays are used.

Voltage and current samples are taken continuously to monitor the fault condition. These samples are taken by a powerful data acquisition module Advantech USB-4711A connected to the USB port. Values of R and L are obtained from these voltage and current samples by differential equation principle. If the impedance seen by the relay is inside the quadrilateral, then software further checks for the fault lying at a particular zone and sends trip signal for that zone.

II. PROTECTION OF TRANSMISSION LINE

The impedance of a transmission line is proportional to its length, for distance measurement it is appropriate to use a relay capable of measuring the impedance of a line up to a predetermined point (the reach point). Such a relay is described as a distance relay and is designed to operate only for faults occurring between the relay location and the selected reach point, thus giving discrimination for faults that may occur in different line sections.

The basic principle of distance protection involves the division of the voltage at the relaying point by the measured current. The apparent impedance so calculated is compared with the reach point impedance. If the measured impedance is less than the reach point impedance, it is assumed that a fault exists on the line between the relay and the reach point. The reach point of a relay is the point along the line impedance locus (set of points) that is intersected by the boundary characteristic of the relay. Since this is dependent on the ratio of voltage and current and the phase angle between them, it may be plotted on an R/X diagram. The loci of power system impedances as seen by the relay during faults, power swings and load variations may be plotted on the same diagram and in this manner the performance of the relay in the presence of system faults and disturbances may be studied.

As the power systems become more complex and the fault current varies with changes in generation and system configuration, directional over current relays become difficult to apply and to set for all contingencies, whereas the distance relay setting is constant for a wide variety of changes external to the protected line. Impedance relays are used whenever over current relays does not provide adequate protection. They function even if the short circuit current is relatively low. The speed of operation is independent of current magnitude.

III. NUMERICAL RELAY

Electric power utilities traditionally use electromechanical and solid-state relays for protecting distribution and sub-transmission systems. With advances in technology, protective relays have progressed from electromechanical, to solid state and to microprocessor-based relays. The increased growth of power systems both in size and complexity has brought about the need for fast and reliable relays to protect major equipment and to maintain system stability. With the development of economical, powerful and sophisticated microprocessors, there is a growing interest in developing microprocessor-based protective relays, which are more flexible because of being programmable and are superior to conventional electromagnetic and static relays. Fig. 1 shows the block diagram of numerical relay. The main features which

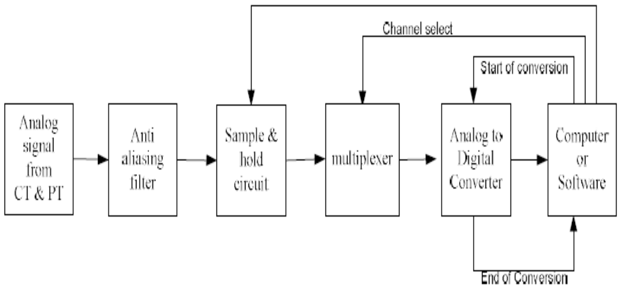

Fig. 1. Block diagram of numerical relay

have encouraged the design and development of microprocessor based protective relays are their economy, compactness, reliability, flexibility and improved performance over conventional relays [2]. The main components of numerical relay are-

- Anti-aliasing filter
- Sample and hold circuit
- Multiplexer
- A to D converter
- Processor

IV. NUMERICAL THREE STEPPED DISTANCE PROTECTION SCHEME

In order to cover a section of the line and to provide back-up protection to remote sections, three main protection zones are set up with the following criteria [3]. Fig.2 shows different zones of three stepped distance relay.

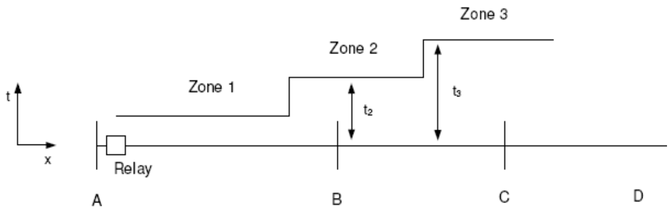

Fig.2. Three stepped Distance-relay protection zones

- Zone 1: this is set to protect between 80% of the line length AB.
- Zone 2: this is set to protect 100% of the line length AB, plus at least 50% of the shortest adjacent line BC and operates with time delay t2.
- Zone 3: this is set to protect 100% of the two lines AB, BC, plus about 25% of the third line CD and operates with time delay t3.

In the project the starting element will be the quadrilateral distance measuring element. It is not affected by the arc resistance and least affected by the power swing. The remaining two elements will be reactance measuring elements as shown in Fig. 3. Quadrilateral distance relay is used for third step and reactance relay for first and second steps.

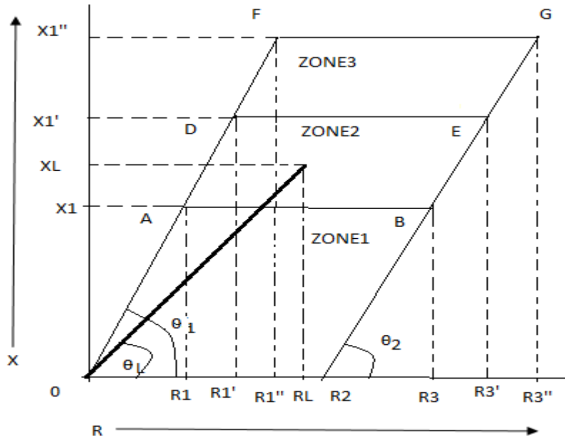

Fig.3. Three stepped distance relay characteristics

If the impedance seen by the relay is inside OABR2, then it lies in zone1 and instantaneous tripping command is issued with tripping time t1. And if it is inside ADEB, then it lies in zone2 and tripping command is issue with tripping time t2 which is equal to t1+Δt. And if it is inside DFGE, then it lies in zone3 and tripping command is issued with tripping time t3 which is equal to t2+Δt. Each of these zones can be defined as:

- Slope of line AF= slope of line characteristic on R-X diagram without arc resistance= $m1=\tan\theta 1$
- Slope of line R2G= slope of line characteristic on R-X diagram with arc resistance= $m_2=\tan\theta 2$
- Line AB=k_1
- Line DE=k_2
- Line FG=k_3

During fault if resistance and inductance up to the fault point are known then trip condition can be decided. In this project for development of the relay characteristic, differential equation principle is used which calculates the impedance i.e. R and X of the line.

V. ADVANTECH DEVICE USB-4711/A

The Advantech USB4711/A is a powerful data acquisition (DAS) module for the USB port. It features a unique circuit design and complete functions for data acquisition and control. This device is used in this project to read real time voltage and current signals and to generate numerical three stepped distance relay characteristic. This device samples the input signal through analog input channel, provides the reading of these signals in analog and digital form, and issue the trip signal generated by relay software which is written in Visual Basic 6.0.

Following are the features of Advantech USB-4711[4]:

- 16 single-ended analog input channels
- 12-bit resolution A/D converter, with up to 100 kS/s sampling rate
- 8 digital input & 8 digital output channels (TTL Level)
- 2 analog output channels
- Automatic channel/gain scanning
- On-board 1K samples FIFO buffer for AI channels

- No need for external power
- Device status LED indicator
- Removable on-module wiring terminal
- Supports high-speed USB 2.0
- Auto calibration function
- Hot swappable

VI. IMPLEMENTATION OF NUMERICAL THREE STEPPED DISTANCE RELAY

In the numerical relay, analog signals i.e. voltage and current signals are processed through the series of hardware blocks and finally given to the computer/processor (in digital form), where the software processes the digital signal and takes decision for tripping. Fig.4 shows the block diagram of numerical three stepped distance relay.

Fig.4. Block diagram of numerical three stepped distance relay

In Fig.4, V_R and I_R are the relay voltage and relay current respectively. Both these signals are supplied to the computer through hardware. The hardware part mainly consist of data acquisition (DAS) module USB4711/A. This is an automation module that will be used in this project to route the real time voltage and current signals to the computer. This device samples the voltage and current signal, converts it into digital form and sends it to the computer where software processes these signals. Software computes the impedance (reactance and resistance) and takes decision for tripping according to the principle of three stepped distance protection scheme.

The research and analysis work done till now for the quadrilateral and three stepped distance relay have been suffering from errors occur during data acquisition. Since the researchers have used electronics based hardware, op-amp and transistor based circuits to read data. This paper presents an application of a powerful data acquisition module i.e. Advantech device USB4711/A which has high level of accuracy of data conversion and high speed data sampling capacity.

A. Algorithm

- Read values of analog voltage and current from its respective channels for four successive instants.
- Calculate R and X
- Check if it lies in quadrilateral distance relay i.e. X>0 and X<k3 and X<(m1*R) and X>(m2*R +c)
- Further if it lies in quadrilateral then check for different zones.
  - ✓ If X<0 and X<k1 then zone1 is tripped instantaneously.
  - ✓ If X>k1 and X<k2 then zone2 is tripped with time delay of 5 second.
  - ✓ Otherwise zone3 is tripped with time delay of 10 second.
- Otherwise system is healthy.

B. Relay Software

The software for the development of three stepped distance relay characteristic is developed with the help of programming tool i.e. VISUAL BASIC 6.0. The Advantech Device Drivers works seamlessly with development tools such as Visual C++, Visual Basic, Inprise C++ Builder, and Inprise Delphi. [5]

The developed software read two analog inputs i.e. voltage and current from analog input channel of Advantech Device with a sampling window of four samples. From instantaneous values of these analog inputs of one window, values of R and X are calculated. Then in order to generate the relay characteristic, software compares values of R and X as explained in algorithm. Based on conditions, software issue trip signal or takes another four samples of voltage and current and continues same operation. Fig. 5 shows the main window of the software.

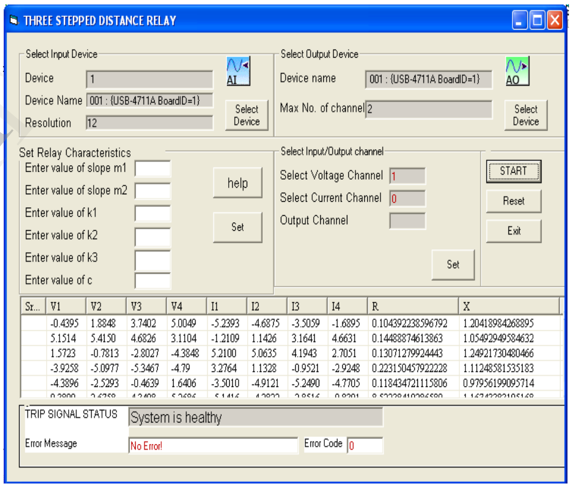

Fig.5. Main window of three stepped distance relay

C. Testing of relay software

The equipments used for the testing purpose are as follows-

- Function generator to generate test signal
- Digital Storage Oscilloscope (DSO) to see nature, magnitude and phase shift between two analog signals.
- Power Supply of +/-12V
- Phase shifter circuit LM741
- Automation module- Advantech Device USB4711/A
- Computer

It was necessary to validate the characteristic generated by software. For testing purpose hardware is required to provide variable voltage, variable current and variable phase shift between them. Fig. 6 shows the block diagram of test set-up. From function generator sinusoidal signal is generated. And with the help of two pot these voltage and current signals are varied. With the help of phase shifter circuit, angle of current is varied from 0° to 90°. Hence two signals i.e. $V_R\angle 0°$ and $I_R\angle \Theta$ are fed to the USB4711/A device which is connected to computer through USB port.

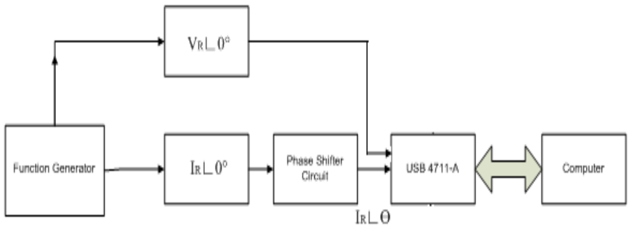

Fig.6. Block diagram of test set-up

From analog input channel i.e. channel no. AI0 voltage samples and from channel no. AI1 current samples have been taken and ground is provided at analog ground channel i.e. AGND. These two analog inputs are fed to the computer through Advantech Device. The software checks the conditions to generate three stepped distance relay characteristic and if the conditions are satisfied then trip signal is given.

D. Three stepped distance relay setting

A transmission line with following parameters is assumed for the protection.

R=0.3 Ω/km
L=3.5 mH/km
X=1.12 Ω/km
CTR=1000/5
PTR=132kV/5V

$Z_{sec}=Z_{prim}$ *CTR/PTR
Z_{sec}= (Z_{prim}*1000*5)/ (5*132*1000) = Z_{prim}/132
=0.00758 Z_{prim}
Length of section AB=125 km
Length of section BC=100km
Length of section CD=80km
X_I=0.8*125*X=100(j1.112)
=j112 Ω
X_{II}= (125+0.5*100)*X=175(j1.112) Ω
X_{III}= (125+100+0.25*80)*Z=245(0.3+j1.12) Ω
=73.5+j274.4 Ω
=284.073∟75.005° Ω

Relay setting (reach from secondary side of PT and CT) will be-
X_I=j112*0.00758= j0.848 Ω
X_{II}=j196*0.00758=j1.485 Ω
Z_{III}=(284.073∟75.005°)*0.00758
=0.557+2.079j= R_{III}+jX_{III}
=2.153∟75.005° Ω
$Z_{III}|_{w/o}$=2.153∟75.005 Ω
R_{arc}=15 Ω from primary side
R_{arc}(from primary)=15Ω
R_{arc}(from secondary)=15*0.00758
=0.1137Ω
$Z_{III}|_{with}$=0.557+2.079j+ R_{arc} (from secondary)
= 0.557+2.079j+0.1137
=0.6707+2.079j
=2.184∟72.119°
$Z_{III}|_{with}$=2.184∟72.119°
m_1=tan∟$Z_{III}|_{w/o}$= tan∟75.005°= 3.733
m_2=tan∟$Z_{III}|_{with}$= tan∟72.119°= 3.099
X_I=0.848j Ω
X_{II}=1.485j Ω
X_{III}=2.079j Ω
Where Z_{prim}= impedance of the line from primary side
Z_{sec}= impedance of the line from secondary side i.e. relay side
R_{arc}= arc resistance
$Z|_{with}$=reach of the relay with arc resistance
$Z|_{w/o}$= reach of the relay without arc resistance
m1= Slope of line characteristic on R-X diagram without arc resistance
m_2= Slope of line characteristic on R-X diagram with arc resistance

Hence from above assumptions, the values of m_1, m_2, k_1, k_2 and k_3 are set as follows:

- Slope, m_1=3.733
- Slope, m_2=3.099
- Constant k_1=0.848=|XI|
- Constant k_2=1.485=|XII|
- Constant k_3=2.079=|XIII|

And c is calculated from line segment equation i.e. (y_2-y_1) =m(x_2-x_1). Hence constant c=-0.37.

VII. RESULTS

A. 1st set of experiment

The current signal I R is kept constant i.e. I_R=5A. For different values of phase angle (0° to 72°; increased in step of 12°), the voltage V_R for tripping the relay at different zones is obtained. Results are as shown in TABLE I.

B. 2nd set of experiment

The voltage signal V_R is kept constant i.e. V_R=1V. For different values of phase angle (0° to 72°; increased in step of 12°), the current I_R for tripping the relay at different zones is obtained. Results are as shown in TABLE II.

C. 3rd set of experiment

The phase angle between the signals i.e. Φ is kept constant. Keeping I_R constant, V_R is varied so that Z_R varies. Hence, Z_R corresponding to different zones gives results as shown in TABLE III.
Φ=72°;
I_R=1A
Zone 1 reach, $Z_{1-reach}$=0.9Ω
Zone 2 reach, $Z_{2-reach}$=1.65Ω
Zone 3 reach, $Z_{3-reach}$=2.2Ω

TABLE I. I_R=5A

Phase angle Φ	Vcal	Vobs	Rcal	Robs	Xcal	Xobs	Zcal	Zobs	Zone
0°	0.57	0.56	0.114	0.112	0	0	0.114	0.112	1
12°	0.65	0.64	0.127	0.125	0.027	0.026	0.13	0.128	1
24°	0.75	0.72	0.137	0.132	0.061	0.058	0.15	0.144	1
36°	0.95	0.89	0.154	0.144	0.112	0.104	0.19	0.178	1
48°	1.35	1.52	0.181	0.203	0.201	0.226	0.27	0.304	1
60°	2.55	2.48	0.255	0.248	0.442	0.429	0.51	0.496	1
72°	10.9	11.8	0.674	0.729	2.073	2.244	2.18	2.36	3

TABLE II. V_R=1V

Phase angle Φ	Ical	Iobs	Rcal	Robs	Xcal	Xobs	Zcal	Zobs	Zone
0°	8.77	8.4	0.114	0.119	0	0	0.114	0.119	1
12°	7.69	7.2	0.127	0.135	0.027	0.028	0.13	0.138	1
24°	6.67	6.68	0.137	0.136	0.061	0.06	0.15	0.149	1
36°	5.26	5.2	0.154	0.155	0.112	0.113	0.19	0.192	1
48°	3.7	3.8	0.181	0.196	0.201	0.195	0.27	0.263	1
60°	1.9	1.88	0.255	0.266	0.442	0.46	0.51	0.531	1
72°	0.46	0.48	0.674	0.644	2.073	1.981	2.18	2.083	3

TABLE III. Φ=72°; I_R=1A

S.No.	V_R	Z_R	Zone	Action
1	0.7	0.7	1	Instantaneous tripping occurs
2	1.4	1.4	2	Tripping occurs after 5sec. Delay
3	2.08	2.08	3	Tripping occurs after 10sec. Delay
4	3.2	3.2	Beyond Quadrilateral	No tripping occurs since healthy system

Where V_{cal}, I_{cal}, R_{cal}, X_{cal}, Z_{cal} are calculated values of voltage, current, resistance, reactance and impedance respectively. V_{obs}, I_{obs}, R_{obs}, X_{obs}, Z_{obs} are observed values of voltage, current, resistance, reactance and impedance respectively.

From TABLE I and TABLE II, it is clear that experimentally performed results are matching with the calculated results. Tripping occurs according to the conditions provided to the relay characteristic in the software as shown in TABLE III. Hence the software and hardware developed for three stepped distance relay characteristic is working satisfactorily.

VIII. CONCLUSION

The relay software is able to trip at different zones and is able to distinguish between faulty condition and healthy condition. In the developed three stepped distance relay characteristic there is a provision to change the values of characteristic parameters. Tested results are matching with the calculated results. Hence it is concluded that the developed numerical three stepped distance relay is working satisfactorily.

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