Adaptive and intelligent relaying schemes for power transmission networks

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JULY 2016

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by

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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2016

I would like to dedicate this thesis to my loving family & teachers …

CERTIFICATE

This is to certify that the thesis entitled **“ADAPTIVE AND INTELLIGENT RELAYING SCHEMES FOR POWER TRANSMISSION NETWORKS”** being submitted by **Mr. Rahul Kumar Dubey** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirements for the degree of Doctor of Philosophy. The results contained in this thesis have not been submitted, in part or full, to any other University or Institute for the award of any degree or diploma.

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Acknowledgements

I am grateful to my advisor, Dr. B. K. Panigrahi, Dr. S. R. Samantaray and Dr. Vijendran G. Venkoparao, who gave me the opportunity to realize this work in the laboratory. They encouraged, supported and motivated me with much kindness throughout the work. In particular, they showed me the interesting side of the power system engineering and those of the highly interdisciplinary project work. I always had the freedom to follow my own ideas, which I am very grateful for. I really admire them for patience and staying power to carefully read the whole manuscript.

I would like to express my sincere gratitude to my committee members, Dr. Nilanjan Senroy and Dr. Abhijit R. Abhyankar, who contributed immensely to this thesis by their valuable suggestions. I would like to thank the head of Electrical engineering department, Prof. Bhim Singh, faculty members of the power systems group and staff members for their unparalleled academic support. I also acknowledge all staffs, research scholars, friends and juniors of the power system simulation lab, Electrical Engineering Department, IIT Delhi for their kind co-operation, support and encouragement during the entire course of this research work.

This research work is supported by the Prime Minister's Fellowship for Doctoral Research and being implemented jointly by Science & Engineering Research Board (SERB) and Confederation of Indian Industry (CII), with industry partner Robert Bosch. I acknowledge all staffs, and researcher of Robert Bosch Research & Technology Center (RTC) Koramangala, Bengaluru for helping me during my research work.

I render my respect to all my family members for giving me mental support and inspiration for carrying out my research work.

Rahul Kumar Dubey

Abstract

Transmission network is heart of the power system and needs reliable protection measure against fault and similar disturbances. The protection system must detect and clear the faulty section as soon as possible from rest of the power system and prevent the power system from blackouts. Distance Relays are the most widely used relays in transmission network for effective protection measure. Primarily, the voltage and current signals are retrieved at the relaying locations and fed to the protective relays for relaying decision to issue the tripping signal. In case of faults, outage or some disturbances in the system, the relays should be selective in issuing the appropriate signal to the circuit breaker or other relay to separate the faulty section or apparatus from the rest of the power system. There are various types of relay used in protection schemes and are mainly classified into electromechanical, solid state and digital relays. Electromechanical relays are based on electro-mechanical torque which is produced by the actuating quantities such as voltage and current and, close the tripping contact by mechanical movement. Solid state relays utilize linear and digital integrated circuits for implementation of logic functions and signal processing to trigger the tripping signal. The most modern relays are digital relays which are in use since last two decades. These relays include various functions such as analog to digital conversion of the input analog signals, computing the relaying faction and issuing the tripping signal. Various functions of the digital relays are implemented on microprocessors or Digital Signal Processors. Distance relays measure the impedance between the relaying point and the faults and, the relays respond to the faults inside the zone of protection and remain inhibited to the faults outside the intended range of protection zone. Even though the distance relay is widely used, however the reach of the relay may be affected due to variations in system operating conditions such as fault location, fault resistance etc. Various studies have been done to accurately set the tripping characteristic of a distance relay during aforementioned issues.

The use of Flexible AC Transmission Systems (FACTs) and off-shore wind farms are gaining momentum in modern power transmission network to extend the power transfer capability without going for expansion planning. Even if the inclusion of FACTs and wind-integration improves operational aspects, on the other hand the protection system faces becomes serious challenges. Most versatile FACTs device which has attracted wide-spread attention is the Unified Power Flow Controller (UPFC), which improves the transient stability. However, presence of UPFC in a fault loop affects the voltage and current signals at the relay point, which in turn affects the tripping characteristics of the relay. The problem is further compounded when wind-farm is integrated to the transmission network. Due to uncertain wind speed variation, the relaying end voltage fluctuates continuously and the tripping boundaries of the relay get affected. Thus, generating adaptive relay tripping characteristics, is one of the most challenging issues for transmission line distance relays as the present day transmission systems is subjected to more stressed environment with respect to power system operation. Thus, inclusion of FACTs devices such as SVC, STATCOM, SSSC and UPFC seriously impact the performance of the distance relays as the apparent impedance changes and the reach setting of the relay is significantly affected due to integration of off-shore wind-farms integrated to power transmission system. Thus, generating adaptive tripping characteristics of the distance relay for appropriate operating conditions is a demanding concern and the same is addressed in the proposed research work.

In this thesis, some important issues on adaptive distance protection scheme for FACTS-compensated line such as SVC, STATCOM and UPFC connecting with wind farm are addressed. A new machine intelligence technique such as Extreme Learning Machine and On-line Sequential Extreme Learning is used to develop fast and accurate stand-alone intelligent digital distance relaying scheme for both general transmission line and line including advanced series-FACTS device such as SSSC are extensively studied and improved results are derived. Further, a new approach for power transmission network protection to enhancing the distance relay performance during stress condition such as power swing and load encroachments has been proposed in this thesis. Finally, wide-area information is considered to make the relaying scheme more reliable and intelligent.

Contents

List of Figures

List of Tables

Nomenclature

Single circuit line with UPFC

E_{aw} : Phase-a wind source voltage

E_{an} : Phase-a grid voltage

V_{aw} : Phase-a voltage at bus 'W' where the relay is present

V_{an} : Phase-a voltage at bus 'N'

V_{as1} : Phase-a voltage at bus S_1

V_{as2} : Phase-a voltage at bus S_2

E_{sh} : Shunt voltage of UPFC

$re^{j\theta}$: A factor for series voltage of UPFC (r is the % injected voltage and θ is series injected voltage phase angle is in degree)

h_1 : Voltage amplitude ratio (V_{as1}/ E_{aw})

I_{aw} : Phase-a current at the relaying point 'W'.

I_{0w} : Phase-a zero sequence current at the relaying point 'W'.

I_{1wf} : Phase-a positive sequence current of line between bus 'W' & fault point 'F'

I_{2wf} : Phase-a negative sequence current of line between bus 'W' & fault point 'F'

I_{ld} : Pre-fault current in the line without UPFC.

I_{0f} : Phase-a zero sequence fault current.

δ_1 : Loading level of wind farm.

K_0 : Zero sequence compensating factor.

Z_{1sw} : Positive sequence source impedance of wind farm

Z_{0sw} : Zero sequence source impedance of wind farm

Z_{1sn} : Positive sequence source impedance of grid

Z_{0sn} : Zero sequence source impedance of grid

Z_{1wn} : Positive sequence impedance of line between bus 'W' & 'N'

Z_{0wn} : Zero sequence impedance of line between bus 'W' & 'N'

Z_{1ws1} : Positive sequence impedance of line between bus 'W' & 'S_1'

Z_{0ws1} : Zero sequence impedance of line between bus 'W' & 'S_1'

Z_{1ns1} : Positive sequence impedance of line between bus N & S_1

Z_{0ns1} : Zero sequence impedance of line between bus N & S_1

Z_{1wf} : Positive sequence impedance of line between bus W & fault point F

Z_{0wf} : Zero sequence impedance of line between bus W & fault point F

Z_{1nf} : Positive sequence impedance of line between bus N & fault point F

Z_{0nf} : Zero sequence impedance of line between bus N & fault point F

Z_{1s1f} : Positive sequence impedance of line between bus S_1& fault point F

Z_{0s1f} : Zero sequence impedance of line between bus S_1 & fault point F

Z_{1s2f} : Positive sequence impedance of line between bus S_2 & fault point F

Z_{0s2f} : Zero sequence impedance of line between bus S_2& fault point F

$Z_{\sum}$: Sum of total positive-, negative-, and zero-sequence impedances

The positive and zero sequence impedance from 'W' side are

$Z_{1swf} = Z_{1sw} + Z_{1wf}$

$Z_{0swf} = Z_{0sw} + Z_{0wf}$

Similarly, the positive and zero sequence impedance from 'N' side are

$Z_{1snf} = Z_{1sn} + Z_{1nf}$

$Z_{0snf} = Z_{0sn} + Z_{0nf}$ and Z_{s1} : Shunt impedance of UPFC

a- Stands for a-phase as the calculations are for line-to-ground (L-G) fault condition.

0- Stands for zero sequence

1- Stands for positive sequence

2- Stands for negative sequence

Double circuit line with UPFC

E_{AW} : Wind source voltage for system

E_{AN} : Grid voltage

h : Voltage amplitude ratio for system

δ : Loading level of wind farm

λ_{0T} : Line zero-sequence compensation factor for system

Z_{1SW} : Positive sequence source impedance of wind farm

Z_{0SW} : Zero sequence source impedance of wind farm

Z_{1SN} : Positive sequence source impedance of grid

Z_{0SN} : Zero sequence source impedance of grid

Z_{1T1} : Positive sequence impedance of line-1

Z_{1T2} : Positive sequence impedance of line-2

Z_{0T1} : Zero sequence impedance of line-1

Z_{0T2} : Zero sequence impedance of line-2

Z_{0WU} : Zero sequence mutual impedance of system

n : The proportion of the line section from the relaying point W to the fault point F

$Z_{\sum}$: Sum of total positive , negative , and zero sequence impedances

V_{AS1} : Phase-A voltage at bus S1

V_{AS2} : Phase-A voltage at bus S2

V_{ASH} : Shunt voltage of UPFC

ρ:Voltage amplitude ratio (V_{AS1}/ E_{AW})

G_{SH}:Voltage ratio (V_{AS1}/ V_{ASH})

I_{WS1}, I_{WS2} : Pre-fault phase-A current

V_{AFD}: A-phase voltage at the fault point

Z_{1WF} : Positive sequence impedance of line between bus W & fault point F

I_{0F}: Zero sequence component of fault current

I_{AW}: Current at bus W where the relay is present

V_{AW}: Voltage at bus W where the relay is present

I_{AS2F}: A-phase fault current at S2 (UPFC injection bus)

A-Stands for a-phase as the calculations are for line-to-ground fault condition.

Single circuit line with STATCOM

x: Fault location

R_f: Fault resistance

I_f: Fault current

$V_{prefault\_f}$: Pre-fault voltage

$V_{postfault\_R}$: Post-fault voltage

I_{relay}: Relay current

Z_1, Z_2 and Z_0 : Positive, negative and zero sequence equivalent impendence

Z_{1s}, Z_{2s} and Z_{0s} :Positive, negative and zero sequence sending end source impendence

Z_{1r}, Z_{2r} and Z_{0r} :Positive, negative and zero sequence receiving end source impendence

I_1, I_2 and I_0 : Positive, negative and zero sequence current

V_{ref} and V_{HV} : Reference and high voltage for SVC

Z_{xr0}: Zero sequence shunt impedance of SVC

Z_{SVC}: Equivalent impedance of SVC

$Z_{STATCOM}$: Equivalent impedance of STATCOM

$Z_{APPARENT}$: Equivalent apparent impedance

Three source network

E_{sm} : Source-1 voltage

E_{sx} : Source-2 voltage

E_{sn}: Source-3 voltage

Z_{0L1} : Zero sequence impedance of line-1

Z_{1L1} : Positive sequence impedance of line-1

Z_{0L2} : Zero sequence impedance of line-2

Z_{1L2} : Positive sequence impedance of line-2

Z_{0L3} : Zero sequence impedance of line-3

Z_{1L3} : Positive sequence impedance of line-3

Z_{1sm} : Positive sequence source-1 impedance

Z_{0sm} : Zero sequence source-1 impedance

Z_{1sx} : Positive sequence source-2 impedance

Z_{0sx} : Zero sequence source-2 impedance

Z_{1sn} : Positive sequence source-3 impedance

Z_{0sn} : Zero sequence source-3 impedance

Z_{c1} : Shunt impedance of line-1

Z_{c2} : Shunt impedance of line-2

Z_{c3} : Shunt impedance of line-3

x : Fault location (0 to 80%)

R_f : Fault resistance (0Ω to 200Ω)

Single circuit line with SSSC

$V_{prefault\_f}$: The pre-fault voltage at the fault point '*f*' $I_{prefault\_R}$: The load current seen by relay before fault

V_{SSSC}: SSSC voltage $\left(V_{SSSC} = V_{S1} + V_{S2} + V_{S0}\right)$

$Z_{SSSC} = V_{SSSC}^2 / P_{SSSC}$: The impedance of SSSC

$V_{postfault\_R}$: The post fault voltage seen by relay

1, 2 & 0 subscripts denote the positive sequence, negative sequence & zero sequence quantities.