RELAY COORDINATION IN DISTRIBUTION SYSTEMS WITH AND WITHOUT DISTRIBUTED ENERGY RESOURCES

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by

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CERTIFICATE

This is to certify that the dissertation entitled **"RELAY COORDINATION IN DISTRIBUTION SYSTEM WITH AND WITHOUT DISTRIBUTED ENERGY RESOURCES"** being submitted by **Mr. Manohar Singh f**or the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering at Indian Institute of Technology, New Delhi

Mr Manohar Singh has worked under my supervision and guidance and has fulfilled the requirements for the submission of this dissertation, which to my knowledge has reached the requisite standard. The results obtained here have not been submitted to any other University or Institute for the award of any degree.

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ABSTRACT

Rapid urbanization and fast industrial growth in last few decades has caused exponential expansion of power networks both at sub-transmission and distribution levels. The configuration of distribution networks is continuously changing with growth of new load centres and direct connection of new distributed energy resources (*DER*). Direct connections of *DERs* in the distribution systems have both merits and demerits from power economics and distribution system operation and control point of view. Operation, control and protection of distribution system become very complicated and challenging for the protection engineers, when *DERs* are directly connected with them. The proposed research work in this thesis is particularly focussed on the relay coordination issues in the distribution system with and without *DER*.

A fault in any section of distribution system causes outage of power lines. Protection schemes are provided in the distribution systems for quick disconnection of faulty section from the remaining healthy portion of power system. Main aim of protection schemes is to restrict the fault spread, so that minimum outage of power lines should occur. Conventionally distribution lines and feeders are protected by over current relays. Over current relays are used in primary as well as in backup protection schemes for the distribution networks. However, slow operational speed of over current relays is not a desirable feature for their application in primary protection schemes for sub transmission systems. In such power systems, distance relays are ideal choice for primary protection schemes and over current relay are used in back up protection schemes.

In interconnected power networks, for each fault location on a line, relays are installed at both near end bus and far end bus. The relay which is supposed to clear the fault first is known as primary relay. In over current relay coordination studies, failure of one over current relay is backed with other over current relays. The relay which is operating when

the main relay fails to operate is known as backup relay. In a properly relay coordinated scheme, for a fault on the line, the primary relay at either near end bus or far end bus should operate before their corresponding backup relays. However, when primary relays fails to operate due to any reasons, and then corresponding backup relays should operate within a desired time interval to minimize the impact of fault currents on the power systems. This thesis, proposes a modified over current relay coordination algorithm, which is optimised when lower and upper time limit are put on the coordination time interval between the operation of primary relays and backup relays. Moreover, the performance of existing over current relay coordination algorithms is also improved by use of artificial intelligence based optimization algorithms for big interconnected distribution systems, where conventional optimization algorithm fails to solve the relay coordination problems due to their poor convergence rate.

In practice, depending upon the severity of fault and distance of fault point for the relay location, some other over current relays may trip which are not associated with that particular fault. This unwanted operation of over current relays is known as sympathetic tripping. Sympathetic trippings causes loss of healthy power system lines and adversely affects the reliability of the power systems. These types of tripping are challenge for proper operation and control of distribution systems. In this thesis, a novel relay coordination algorithm is proposed, which is immune to all types of sympathetic tripping. Partial clearance of fault from one end in an interconnected distribution system may leads to maloperation of over current relays due to redistribution of fault currents during transient network topology period. In this thesis, the relay coordination algorithm is modified to decrease the chance of existence of transient network topology. This is achieved in this thesis by minimizing the operating time gap between the primary relays at near end and far end buses within best possible minimum time margin.

Injections of *DER* in distribution system jeopardize the existing protection coordination schemes. Impact depends upon number, size, type and location of *DER* in the distribution systems. Moreover, the location of *DER* in distribution system changes the configuration of distribution systems. Generally, the distribution systems are radial in nature and over current based protection schemes are set for unidirectional flow of fault currents. Injection of *DER* usually causes meshed configuration of distribution systems and on majority of distribution feeders, fault current flows in both directions. Generally existing protection coordination schemes are based on unidirectional flow of fault currents. Hence, they are unable to provide the adequate protection coordination when *DER* power injected in the distribution systems.

Each new incoming *DER* causes change in the existing network topology of distribution systems. Requirement of additional direction over current relays depends upon the location of new incoming *DER* in the distribution systems. New combination of primary/backup over current relays come into existence due new incoming additional directional overcurrent relays in the distribution systems. Therefore, an algorithm is developed in this thesis to identify the correct combination of backup relays for each primary over current relay when the topology of the network changes due to incoming *DER.*

Two basic relay coordination techniques are presented in this thesis for restoration of relay coordination in distribution systems during *DER* penetration. One technique is based on adaptive protection scheme. In this relay coordination scheme, over current relays are identified which are involved in over current relay maloperation due to *DER* connection in the distribution systems. Settings of these relays are re-optimized as per the requirement of relay coordination scheme of the distribution system with *DER.* In other non-adaptive over current relay coordination technique, the impact of *DER* power in the distribution system is nullified with the help of fault current limiter (*FCL*) and relay setting remains unaltered to their without *DER* status settings. In order to optimize the size of *FCL* required in non-adaptive relay coordination scheme and number of relay re-optimization required in adaptive relay coordination scheme, a hybrid protection coordination scheme is proposed in this thesis to maintain the overcurrent relay coordination in distribution systems with *DER* injection. The proposed hybrid over current relay coordination scheme requires small size of *FCL* and less number of relay are re-optimized as compare to above two mentioned relay coordination schemes.

Generally, the distribution system operators are not willing to change the relay settings for each new incoming *DER* or any change in network topology. But in reality relays required new relay settings whenever the fault level changes in the network. In this thesis, an algorithm is proposed which is based on adaptive relaying scheme. In this algorithm, all possible network topologies are identified initially and corresponding optimal relay settings are obtained and stored in groups. Each group corresponds to a particular network topology. In the online phase of proposed relay coordination algorithm, the prevailing network topology is identified by monitoring the status of all circuit breakers and prefault power flow on the lines. Whenever the network topology changes, the desired relay settings group is selected from the initially optimised groups of relay settings and settings are transferred to the individual relay. In this way the relay coordination is maintained among the over current relays whenever there is any change in the fault levels in the networks.

At the end of the thesis, the contribution form the thesis and future scope of the proposed research work is also presented.

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List of Symbols

B	Number of branches
f	Function
FL	Total number of fault location
FCL_{SC}	Superconductive fault current limiter.
I_A	Current seen by relay at bus A
I_B	Current seen by relay at bus B
I_{fl}	Fault current on primary relay side
$I_{maxload}$	Maximum load current
I_i^{max}	Maximum pick up for i^{th} overcurrent relay
I_i^{min}	Minimum pick up for i^{th} overcurrent relay
$I_{i,k}^{p\_near}$	Fault current seen by primary relay for a near end fault
$I_{i,k}^{p\_far}$	Fault current seen by primary relay for a far end fault
I_{infeed}	Infeed current
I_{inst}	Current setting for instantaneous operation of relay
$I_{nominal}$	Nominal load current
I_p	Pick up current
I_{relay}	Current seen by a relay
I_{RES}^k	Fault current of k^{th} renewable energy resource penetration
I_{rtd}	Rated Relay current setting
J	Summation of operating time of all primary relays
$J_{COMDISOCR}$	Combine Fitness function for distance and overcurrent relay coordination

$J_{DIS-OCR}$	Fitness function for distance to overcurrent relay coordination
$J_{modsym1}$	Modified fitness function of elimination of sympathetic trippings
$J_{modsym2}$	Modified fitness function of elimination of sympathetic trippings and minimization of time gap between primary relays at near end and far end.
$J^{P}_{near\_far}$	Summation of operating time of all primary relays at near ends and far ends
$J^{P\_B}_{near}$	Summation of operating time of all primary relays and backup relays
$J_{OCR-OCR}$	Fitness function for overcurrent to overcurrent relay coordination
$J_{OCR-DIS}$	Fitness function for overcurrent to distance relay coordination
$J_{proposed}$	Proposed Fitness function
J_{TDS}	Summation of time dial setting for all overcurrent relays
N_{RES}	Number of renewable energy resources
NR	Number of relay in the power network
$Loss_{BASE}$	Loss in distribution system without renewable energy resource
$Loss_{RES}$	Loss in distribution system with renewable energy resource
L_{RES}	Location of renewable energy resource
N_L	Total number of lines in the network
np	number of directional overcurrent relays involved in sympathetic trippings
OLF	Overload factor
PS_i	Plug setting for i^{th} overcurrent relay
PS_i^{min}	Minimum plug setting for i^{th} overcurrent relay
PS_i^{max}	Maximum plug setting for i^{th} overcurrent relay
PL	Active Power
P_{RES}	Renewable energy power penetration
QL	Reactive Power
$(Pen)_{i,d}$	Penalty generated due to sympathetic trippings of relays

$(Pen)_{i,k}^{near}$	Penalty generated for near end CTI violation
$(Pen)_{i,k}^{near\_far}$	Penalty generated due to critical time margin violation between primary relays at near and far ends
$(Pen)_{i,k}^{far}$	Penalty generated for far end CTI violation
R	Resistance in Ohms
R_FCL	Resistive fault current limiter
R_{FCL}	Maximum resistance of super conducting fault current limiter
R_m	Transient resistance of fault current limiter
S_{RES_k}	Size of i^{th} Renewable energy resource
S_{RES_max}	Maximum Size of i^{th} Renewable energy resource
T_sc	Time constant of fault current limiter
TDS_i	Time dial setting for i^{th} relay
TDS_i^{min}	Minimum limit of time dial setting i, i ϵ NR
TDS_i^{max}	Maximum limit of time dial setting i, i ϵ NR
t_b	Operating time backup overcurrent relay
t_{crc}	Critical time margin between primary relays at near and far ends
t_m	Operating time primary overcurrent relay
t_{oc}	Relay operating time in seconds
T_i^p	Operating time of i^{th} primary relay
$T_{i,k}^{p\_near}$	Operating time of i^{th} near end primary relay for fault at location “k”
t_1	Zone-1 operating time
t_2	Zone-2 operating time
t_3	Zone-3 operating time
$T_{i,k}^{b\_near\_i}$	Operating time of i^{th} near end backup relay for fault at location “k”
$tT_{i,k}^{b\_near\_i}$	Transient operating time of i^{th} near end backup relay for fault at locati“k”
$T_{i,k}^{b}$	Operating time of i^{th} backup relay for fault at location “k”

$T_{i,k}^{b\_far\_i}$	Operating time of i^{th} far end backup relay for fault at location “k”
$tT_{i,k}^{b\_far\_i}$	Transient operating time of i^{th} far end backup relay for fault at location “k”
$T_{i,k}^{p}$	Operating time of i^{th} primary relay for fault at location “k”
$T_{i,k}^{p\_far}$	Operating time of i^{th} far end primary relay for fault at location “k”
T_{m}^{x}	Operating time of any m^{th} non primary/backup relay
tT_{m}^{x}	Transient operating time of any m^{th} non primary/backup relay
V_A	Voltage seen by relay at bus A
v_i	Nodal voltage
w_i	weight factor assigned to the each relay
X_FCL	Reactance fault current limiter
X	Reactance in ohms
z_A	Zone-1 impendence setting of distance relay
z_B	Zone-2 impendence setting of distance relay
Z_FCL	Impedance fault current limiter
z_z	Impendence seen by a distance relay
$\Delta t_{i,k}^{near}$	Coordination time interval between relays for a fault at near end
$\Delta t_{i,k}^{far}$	Coordination time interval between relays for a fault at far end
$\Delta t_{DISOC,k}$	Coordination time margin between distance and overcurrent relay for fault at location “k”
$\Delta t_{OCDIS,k}$	Coordination time margin between over current and distance relay for fault at location “k”
Δt_{near_far}	Coordination time margin between primary relays at near end and far end
Δt_{sym}	Coordination time interval among the overcurrent for sympathetic tripping blocking
$\Delta t_{symtrip}$	Coordination time interval violation among the overcurrent which are operating sympathetically

Acronyms

ABC	Artificial Bees Colony
AI	Artificial Intelligence
ANN	Artificial Neural Network
BBO	Biogeography-Based Optimization
B/ P	Backup/ Primary
BPS	Breakpoint Set
BP	Breakpoints
CGA	Continuous Genetic Algorithm
CTI	Coordination Time Interval
CTIA	Coordination Time Interval Between Primary/Non-Backup Relay Pair
CTIP	Time Margin Between Primary Relays At Near And Far End
CT	Current Transformer
CTR	Current Transformer Ratio
DE	Differential Evolution
DER	Distributed Energy Resources
DNO	Distribution Network Operator
DOCR	Directional Overcurrent Relay
DSA	Differential Search Algorithm

EA	Evolutionary Algorithms
EI	Extremely Inverse
FCL	Fault Current Limiter
GAMS	General Algebraic Modeling System
GA	Genetic Algorithm
HSA	Harmony Search Algorithm
IEC	International Electro-Technical Commission
IEEE	Institute Of Electrical And Electronics Engineers
IDMT	Inverse Definite Minimum Time
IHSA	Improvised Harmony Search Algorithm
LP	Linear Programming
LXPSO	Laplace Crossover Particle Swarm Optimization
MDE	Modified Differential Evolution Algorithm
MINLP	Mixed Integer Non-Linear Programming
NLP	Non-Linear Programming
OCR	Overcurrent Relay
p	Primary Relay
P/B	Primary/Backup Relay Pair
PCI	Protection Coordination Index.
PSO	Particle Swarm Optimization
PSA	Possible Solution Area
PS	Plug Setting

q	Backup Relay
RBFNN	Radial Basis Function Neural Network
RES	Renewable Energy Resources
RSM	Relative Sequence Matrix
RST	Random Search Technique
SI	Standard Inverse
SFCL	Superconducting Fault Current Limiters
SFL	Shuffled Frog Leaping
SQP	Sequential Quadratic Programming
SSFCL	Solid State Fault Current Limiters
SSP	Set Of Sequential Pairs
TCC	Time-Current Characteristic
TDS	Time Dial Settings
TLBO	Teaching Learning Based Optimization
VI	Very Inverse
VLSI	Very Large Scale Integration
WTGS	Wind-Turbine Generator System