

# RELIABILITY COMPLIANT PLANNING AND IMPACT ANALYSIS OF DGs IN DISTRIBUTION SYSTEMS

B. NEELAKANTESHWAR RAO



DEPARTMENT OF ELECTRICAL ENGINEERING  
INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

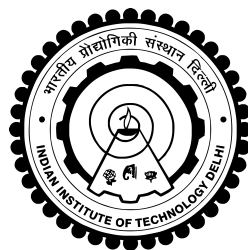
**B. Neelakanteshwar Rao**

Department of Electrical Engineering

Submitted

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to the



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# CERTIFICATE

This is to certify that the thesis entitled, “**Reliability Compliant Planning and Impact Analysis of DGs in Distribution Systems**” being submitted by **Mr. B. Neelakanteshwar Rao** for 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 of Indian Institute of Technology Delhi.

**Mr. B. Neelakanteshwar Rao** has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results obtained here in have not been submitted to any other University or Institute for the award of any degree.

**Dr. A. R. Abhyankar**  
Associate Professor  
Department of Electrical Engineering  
Indian Institute of Technology Delhi  
Hauz Khas, New Delhi - 110016

**Dr. Nilanjan Senroy**  
Associate Professor  
Department of Electrical Engineering  
Indian Institute of Technology Delhi  
Hauz Khas, New Delhi - 110016

**Date:**

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B. Neelakanteshwar Rao

# ABSTRACT

The research work presented in this thesis deals with major issues in planning and one of the most critical issue in operation of distribution system. Loss minimization, economical operation, reliability enhancement and meeting load growth are some of the significant issues in distribution system planning. Impact of wind turbine generators (WTGs) on behaviour of transformer is one of the major issue in operation of the distribution system.

Load in the system is uncertain and time varying in nature. In the existing literature on DG and distribution system planning, a single snapshot of load is usually considered and less attention is given to reliability, deregulation and load growth issues. In this work, DG planning is done by amalgamation of economic and reliability aspects, considering uncertainties in load and market price. Placement of DG deals with issues like availability of various resources and other local constraints. Distribution system operator, who is treated as the policy/decision maker for DG placement in this work, is provided with a set of solutions for DG placement. Depending upon the need, availability of resources and other local constraints, the policy maker can take the decision for DG placement from the proposed set of solutions.

In this work, distribution system planning is done in an economical way, considering load growth, reliability aspects and uncertainties in load, wind and market price. Planning done in this work includes optimal placement of DG, upgradation of distribution network and transformer, considering normal and isolated operations of distributed resources (DG and WTG) and performing reliability analysis. A new approach is proposed for optimal restoration of isolated loads by distributed resources. Distribution system planning is done using genetic algorithm embedded Monte Carlo simulation technique. The proposed approach is applied to 15 and 33-bus distribution systems and the results are analyzed.

Due to advancements in wind system technologies, wind has become one of the promising renewable energy resource. Though, there are many benefits of it, the intermittent nature of wind results in power fluctuations, which ultimately affects the operation of dis-

tribution system components. Node voltages in a distribution system vary with variation in power flows in the system. The on-load tap changer (OLTC) in a transformer responds to the voltage violations and adjusts its tap to regain the voltage within limits. Power fluctuations caused due to intermittent nature of wind can increase the number of tap changes in a transformer. Frequent operation of OLTC increases wear and tear of it and leads to reduction of its life. Failure of a transformer not only affects the economy but also the reliability of the system.

In this thesis, behaviour of OLTC in presence of wind turbine generators, is analyzed using voltage sensitivity analysis under different scenarios and conditions in the distribution system. An approach to improve the voltage sensitivity of a transformer is proposed. Two types of wind turbine generators (WTGs) are used for the analysis; squirrel cage induction generator (SCIG) and doubly fed induction generator (DFIG). The number of tap changes that occur in presence of each type of induction generator is found for an year. The impact of power flows on tap changing is analyzed by selecting critical samples for either cases of generators. The effect of wind speed and the terminal voltage of WTGs on their real and reactive power output is analyzed. An approach to reduce the frequency of tap changes is proposed.

The methodologies suggested in this thesis have been extensively studied on the test systems and detailed discussion has been provided. The results and discussions provide further insights into the nature of the problem addressed.

# Contents

Certificate . . . . .	i
Acknowledgements . . . . .	iii
Abstract . . . . .	v
Contents . . . . .	vii
List of Figures . . . . .	xiii
List of Tables . . . . .	xviii
List of Symbols . . . . .	xxi
Acronyms . . . . .	xxxiii
<b>1 Introduction</b>	<b>1</b>
1.1 Motivation and objective of the present work . . . . .	7
1.1.1 Motivation for the present work . . . . .	7
1.1.2 Research objectives . . . . .	8
1.2 Outline of Thesis . . . . .	9
<b>2 DG Planning Considering Operational, Economic and Reliability As-</b>	
<b>pects</b>	<b>11</b>
2.1 Introduction . . . . .	11
2.2 DG Planning with Amalgamation of Operational and Reliability Consid-	
erations . . . . .	13
2.2.1 Problem formulation . . . . .	16
2.2.1.1 Power balance equations . . . . .	17

2.2.1.2	DG power limits . . . . .	18
2.2.1.3	Node voltage constraints . . . . .	18
2.2.2	Solution methodology . . . . .	18
2.2.2.1	DG placement using LSA . . . . .	19
2.2.2.2	Evaluation of reliability index (ENS) . . . . .	20
2.2.2.3	Evaluation of optimal supply restoration to the isolated load	21
2.2.2.4	Evaluation of performance indices . . . . .	34
2.2.2.5	Evaluation of a combined performance index for decision making . . . . .	36
2.2.3	Results and discussion for DG planning with amalgamation of op- erational and reliability considerations . . . . .	37
2.2.3.1	DG placement in a 15-bus radial distribution system . . .	39
2.2.3.2	DG placement in a 18-bus radial distribution system . . .	42
2.3	DG Planning with Amalgamation of Economic and Reliability Consider- ations . . . . .	45
2.3.1	Problem formulation . . . . .	47
2.3.1.1	Power balance equations . . . . .	49
2.3.1.2	DG power limits . . . . .	50
2.3.1.3	Node voltage constraints . . . . .	50
2.3.2	Solution methodology . . . . .	50
2.3.2.1	Evaluation of performance indices . . . . .	50
2.3.2.2	Evaluation of a combined performance index for decision making . . . . .	52
2.3.3	Results and discussion for DG planning with amalgamation of eco- nomic and reliability considerations . . . . .	53
2.3.3.1	DG placement in a 15-bus radial distribution system . . .	55
2.3.3.2	DG placement in a 18-bus radial distribution system . . .	60
2.4	Optimal Placement of DG using Monte-Carlo Simulation . . . . .	64

2.4.1	Modeling of load uncertainty . . . . .	65
2.4.2	Problem formulation . . . . .	66
2.4.2.1	Bus Voltage limits . . . . .	66
2.4.2.2	DG power limits . . . . .	66
2.4.3	Solution methodology . . . . .	68
2.4.4	Results and discussion for optimal placement of DG using MCS . . . . .	68
2.5	Conclusion . . . . .	73

### **3 Reliability Compliant Distribution System Planning using Monte Carlo**

<b>Simulation</b>		<b>77</b>
3.1	Introduction . . . . .	77
3.2	Literature survey on DSP . . . . .	78
3.3	Some critical issues in DSP . . . . .	80
3.3.1	Reliability aspects in DSP . . . . .	81
3.3.2	Economic aspects in DSP . . . . .	82
3.4	Planning process . . . . .	83
3.4.1	Load Forecasting . . . . .	83
3.4.2	Alternative arrangements to meet the load growth . . . . .	84
3.4.3	Evaluation of alternatives against the desired objectives . . . . .	85
3.4.4	Selection of alternative . . . . .	85
3.5	Problem Formulation . . . . .	86
3.5.1	Power balance . . . . .	87
3.5.2	Line flow limits . . . . .	88
3.5.3	DG power limits . . . . .	88
3.5.4	WTG power limits . . . . .	88
3.5.5	Node voltage constraints . . . . .	89
3.5.6	Net generation available in isolated area . . . . .	90
3.5.7	Isolated priority loads . . . . .	90

3.6	Solution Methodology . . . . .	90
3.6.1	$ENS$ and $C_{ENS}$ evaluation . . . . .	94
3.6.2	$C_{nw}$ , $C_{tf}$ and $C_{EP}$ evaluation . . . . .	97
3.6.3	Evaluation of optimal supply restoration to the load in isolated system	98
3.7	Results and Discussion . . . . .	102
3.7.1	Planning of a 15-bus radial distribution system . . . . .	108
3.7.1.1	DG location and quantum in a 15-bus radial distribution system . . . . .	108
3.7.1.2	Network upgradation in a 15-bus radial distribution system	109
3.7.1.3	Transformer upgradation in a 15-bus radial distribution system . . . . .	111
3.7.2	Planning of a 33-bus radial distribution system . . . . .	113
3.7.2.1	DG location and quantum in a 33-bus radial distribution system . . . . .	113
3.7.2.2	Network upgradation in a 33-bus radial distribution system	114
3.7.2.3	Transformer upgradation in a 33-bus radial distribution system . . . . .	115
3.7.3	Validation of MCS results obtained for 15-bus radial distribution system . . . . .	117
3.7.4	Observations obtained from MCS results for 15-bus radial distribution system . . . . .	118
3.7.4.1	Reliability benefit with varying DG quantum . . . . .	119
3.7.4.2	Reliability benefit with varying wind speed . . . . .	120
3.7.5	Observations obtained from MCS results for 33-bus radial distribution system . . . . .	125
3.7.5.1	Reliability benefit with varying DG quantum . . . . .	125
3.7.5.2	Reliability benefit with varying wind speed . . . . .	126
3.8	Conclusion . . . . .	131

<b>4</b>	<b>Impact of WTGs on Distribution Systems</b>	<b>133</b>
4.1	Introduction . . . . .	133
4.1.1	Wind turbines . . . . .	134
4.1.1.1	Classification of wind turbines based on axis of rotation . . . . .	135
4.1.1.2	Wind turbine power . . . . .	136
4.1.1.3	Wind turbine characteristics . . . . .	137
4.1.2	Wind energy conversion systems . . . . .	139
4.1.2.1	SCIG wind turbines . . . . .	139
4.1.2.2	DFIG wind turbines . . . . .	140
4.1.2.3	FRC wind turbines . . . . .	141
4.1.3	Operational issue with WECS in distribution system . . . . .	143
4.1.3.1	Tap changing Transformers . . . . .	143
4.1.3.2	Resistor and reactor oil-type OLTCs . . . . .	145
4.1.3.3	Factors affecting the tap changing operation of transformer and consequences . . . . .	147
4.2	Analysis of OLTC behaviour in presence of SCIG . . . . .	149
4.2.1	Modelling of a SCIG integrated distribution system . . . . .	150
4.2.1.1	Distribution system feeder modelling . . . . .	151
4.2.1.2	WTG modelling . . . . .	153
4.2.2	Effect of various parameters on behaviour of OLTC in a SCIG in- tegrated distribution system . . . . .	155
4.2.2.1	Variation in VSTC with change in tap position of the transformer . . . . .	156
4.2.2.2	Effect of transformer short circuit MVA on VSTC . . . . .	157
4.2.2.3	Effect of R/X ratio of the line on the behaviour of OLTC transformer . . . . .	158
4.2.2.4	Effect of wind speed on behaviour of OLTC transformer . . . . .	159
4.2.3	Enhancement of VSTC using reactive power compensation . . . . .	161

4.3	Impact of SCIG and DFIG on frequency of OLTC tap changes . . . . .	165
4.3.1	Modelling of WTG integrated distribution system . . . . .	166
4.3.1.1	Turbine modelling . . . . .	166
4.3.1.2	DFIG modelling . . . . .	167
4.3.1.3	SCIG modelling . . . . .	168
4.3.1.4	Distribution Feeder modelling . . . . .	169
4.3.1.5	MPPT operation of DFIG . . . . .	170
4.3.1.6	UPF operation of DFIG . . . . .	170
4.3.2	Evaluation of frequency of OLTC tap changes . . . . .	173
4.3.3	Frequency of OLTC tap changes in presence of SCIG and DFIG . .	173
4.3.4	Some observations on power output of WTGs . . . . .	179
4.3.5	Reduction in frequency of tap changes using reactive power com- pensation . . . . .	181
4.4	Conclusion . . . . .	185
<b>5</b>	<b>Conclusions</b>	<b>187</b>
5.1	Contributions . . . . .	190
5.2	Scope for Future Work . . . . .	192
	<b>References</b>	<b>195</b>
	<b>Appendices</b>	<b>219</b>
	<b>A Input Data and Look up tables</b>	<b>219</b>
	<b>List of Publications</b>	<b>225</b>
	<b>Biodata</b>	<b>227</b>

# List of Figures

2.1	Single line diagram of a 5-bus distribution system . . . . .	19
2.2	Single line diagram of a 5-bus distribution system integrated with DG . . . . .	22
2.3	Fault on branch $b1$ . . . . .	23
2.4	Load restoration using STSA method after a fault on branch $b1$ . . . . .	23
2.5	Fault on branch $b2$ . . . . .	24
2.6	Load restoration using STSA method after a fault on branch $b2$ . . . . .	24
2.7	Fault on branch $b3$ . . . . .	25
2.8	Load restoration using STSA method after a fault on branch $b3$ . . . . .	25
2.9	Fault on branch $b4$ . . . . .	26
2.10	Load restoration using STSA method after a fault on branch $b4$ . . . . .	26
2.11	Single line diagram of a 5-bus distribution system with load switches . . . . .	28
2.12	Flowchart to calculate optimal load dispatchable by DG present in isolated sub-system . . . . .	29
2.13	Fault on branch $b1$ . . . . .	30
2.14	Load restoration using proposed method after a fault on branch $b1$ . . . . .	30
2.15	Fault on branch $b2$ . . . . .	31
2.16	Load restoration using proposed method after a fault on branch $b2$ . . . . .	31
2.17	Fault on branch $b3$ . . . . .	32
2.18	Load restoration using proposed method after a fault on branch $b3$ . . . . .	32
2.19	Fault on branch $b4$ . . . . .	33
2.20	Load restoration using proposed method after a fault on branch $b4$ . . . . .	33

2.21	Flowchart to evaluate performance indices of ENS and TPL . . . . .	35
2.22	Single line diagram of a 15-bus radial distribution system . . . . .	37
2.23	Single line diagram of a 18-bus radial distribution system . . . . .	38
2.24	Percentage load variation with time . . . . .	38
2.25	Performance indices for placement of DG in a 15-bus distribution system .	39
2.26	Combined Performance Index for placement of DG in a 15-bus distribution system . . . . .	40
2.27	Performance indices for placement of DG in a 18-bus distribution system .	43
2.28	Combined Performance Index for placement of DG in a 18-bus distribution system . . . . .	43
2.29	Flowchart to evaluate performance indices of ENS and TC . . . . .	51
2.30	Single line diagram of a 15-bus radial distribution system . . . . .	54
2.31	Single line diagram of a 18-bus radial distribution system . . . . .	54
2.32	Performance Indices for placement of DG in a 15-bus distribution system .	56
2.33	Power delivered by DG placed at various buses in a 15-bus distribution system . . . . .	58
2.34	Performance Index of <i>Ploss</i> for placement of DG in a 15-bus distribution system . . . . .	59
2.35	Combined Performance Index for placement of DG in a 15-bus distribution system . . . . .	60
2.36	Performance Indices for placement of DG in a 18-bus distribution system .	61
2.37	Performance Index of <i>Ploss</i> for placement of DG in a 18-bus distribution system . . . . .	63
2.38	Combined Performance Index for placement of DG in a 18-bus distribution system . . . . .	63
2.39	DG placement using Monte Carlo simulation technique . . . . .	67
2.40	Single line diagram of a 15-bus radial distribution system . . . . .	68
2.41	Single line diagram of a 33-bus radial distribution system . . . . .	69

2.42	Mean and standard deviation values for hourly real power loads at each load bus in a 15-bus radial distribution system [1] . . . . .	70
2.43	Mean and standard deviation values for hourly reactive power loads at each load bus in a 15-bus radial distribution system [1] . . . . .	70
2.44	Mean and standard deviation values for hourly real power loads at each load bus in a 33-bus radial distribution system [1] . . . . .	71
2.45	Mean and standard deviation values for hourly reactive power loads at each load bus in a 33-bus radial distribution system [1] . . . . .	71
3.1	Flowchart to minimize the total cost using genetic algorithm . . . . .	93
3.2	Flowchart for ENS evaluation and network upgradation . . . . .	95
3.3	Flowchart to find minimum and maximum combinations required by load restoration algorithm . . . . .	100
3.4	Flowchart for optimal restoration of the load in isolated system . . . . .	101
3.5	Single line diagram of a 15-bus radial distribution system . . . . .	102
3.6	Single line diagram of a 33-bus radial distribution system . . . . .	103
3.7	Mean and standard deviation values for real power load in a 15-bus radial distribution system [1] . . . . .	105
3.8	Mean and standard deviation values for reactive power load in a 15-bus radial distribution system [1] . . . . .	105
3.9	Mean and standard deviation values for real power load in a 33-bus radial distribution system [1] . . . . .	106
3.10	Mean and standard deviation values for reactive power load in a 33-bus radial distribution system [1] . . . . .	106
3.11	Mean and standard deviation values for hourly LMPs in a 15-bus radial distribution system [2] . . . . .	107
3.12	Scale and shape parameters for hourly wind speeds in a 15-bus radial distribution system [3] . . . . .	107

3.13	Results for DG placement in a 15-bus radial distribution system . . . . .	109
3.14	Results for DG placement in a 33-bus distribution system . . . . .	113
3.15	Load sample corresponding to the solution suggested by MCS . . . . .	119
3.16	Variation in Reliability benefit with varying DG quantum . . . . .	120
3.17	Variation in Reliability benefit with varying wind speed . . . . .	121
3.18	Load sample corresponding to the solution suggested by MCS . . . . .	125
3.19	Variation in Reliability benefit with varying DG quantum . . . . .	126
3.20	Variation in Reliability benefit with varying wind speed . . . . .	127
4.1	Horizontal and Vertical axis wind turbines [4] . . . . .	135
4.2	Typical power curve of a 1500 kW pitch regulated wind turbine . . . . .	138
4.3	Schematic diagram of a SCIG wind turbine generator, [5] . . . . .	140
4.4	Schematic diagram of a DFIG wind turbine generator, [5] . . . . .	141
4.5	Schematic diagram of a FRC wind turbine generator, [5] . . . . .	142
4.6	Compartment and In-tank arrangements of OLTCs [6] . . . . .	144
4.7	Different ways of operating OLTC [6] . . . . .	145
4.8	Design principle of diverter switch (arcing switch) with tap selector [6] . .	146
4.9	Design principle of selector switch (arcing tap switch) [6] . . . . .	147
4.10	Equivalent model of a distribution system integrated with SCIG . . . . .	151
4.11	Reduced equivalent model of a distribution system integrated with SCIG .	151
4.12	Variation of VSTC with change in tap position of OLTC transformer . . .	156
4.13	Variation of VSTC with SCMVA of transformer . . . . .	157
4.14	Variation in VSTC with impedance of the line . . . . .	158
4.15	Variation in VSTC with varying wind speed . . . . .	159
4.16	Variation in sensitivity of current flow with varying wind speed . . . . .	160
4.17	Flowchart to find capacitance required to improve the VSTC . . . . .	163
4.18	Effect of Capacitance on VSTC . . . . .	164
4.19	Capacitance required to improve VSTC . . . . .	164

4.20	Flowchart to perform optimal tap operation and to evaluate node voltages, power supplied by the resources and number of tap changes for varying load and wind speeds . . . . .	171
4.21	Single line diagram of a 33-bus radial distribution system . . . . .	172
4.22	Monthly tap changes in a distribution system with SCIG and DFIG . . . .	174
4.23	Information on tap changes in distribution system with SCIG and DFIG .	176
4.24	Power supplied and demanded for selected samples of input variation in a DFIG integrated distribution system . . . . .	176
4.25	Power supplied and demanded for selected samples of input variation in a SCIG integrated distribution system . . . . .	177
4.26	Variation in power flows and terminal voltages in a transformer for hourly samples of input variation in a system with SCIG . . . . .	178
4.27	Variation in power flows and terminal voltages in a transformer for hourly samples of input variation in a system with DFIG . . . . .	179
4.28	Variations in terminal voltage and output power of a SCIG with wind speed	180
4.29	Variations in terminal voltage and output power of a DFIG with wind speed	181
4.30	Real power flowing through transformer . . . . .	182
4.31	Reactive power flowing through transformer . . . . .	182
4.32	Flowchart to evaluate the capacitance required to reduce the frequency of tap changes and the number of tap changes after compensation . . . . .	183
4.33	Information on tap changes in distribution system with DFIG and before and after compensation in SCIG . . . . .	184

# List of Tables

2.1	Basic reliability indices for failure of branch <i>b1</i> using STSA method . . . .	23
2.2	Basic reliability indices for failure of branch <i>b2</i> using STSA method . . . .	24
2.3	Basic reliability indices for failure of branch <i>b3</i> using STSA method . . . .	25
2.4	Basic reliability indices for failure of branch <i>b4</i> using STSA method . . . .	26
2.5	Load point reliability indices using STSA method . . . . .	27
2.6	Basic reliability indices for failure of branch <i>b1</i> using proposed method . .	30
2.7	Basic reliability indices for failure of branch <i>b2</i> using proposed method . .	31
2.8	Basic reliability indices for failure of branch <i>b3</i> using proposed method . .	32
2.9	Basic reliability indices for failure of branch <i>b4</i> using proposed method . .	33
2.10	Load point reliability indices using proposed method . . . . .	34
2.11	ENS and TPL variation for placement of DG in a 15-bus radial distribution system . . . . .	41
2.12	ENS and TPL variation for placement of DG in a 18-bus radial distribution system . . . . .	44
2.13	ENS and TC variation for placement of DG in a 15-bus radial distribution system . . . . .	57
2.14	ENS and TC variation for placement of DG in a 18-bus radial distribution system . . . . .	62
2.15	Probable solutions for DG placement in a 15-bus distribution system . . .	72
2.16	Probable solutions for DG placement in a 33-bus distribution system . . .	72
3.1	Network upgradation solution for a 15-bus distribution system . . . . .	111

3.2	Transformer upgradation solution for a 15-bus distribution system . . . . .	112
3.3	Network upgradation solution for a 33-bus distribution system . . . . .	116
3.4	Transformer upgradation solution for a 33-bus distribution system . . . . .	117
3.5	Expected value of cost benefit . . . . .	118
3.6	Expected unserved power to the system with wind speed = 6 m/s, $P_{WTG}=0.0284$ MW and $P_{DG}=2.3$ MW . . . . .	122
3.7	Expected unserved power to the system with wind speed = 10 m/s, $P_{WTG}=0.2729$ MW and $P_{DG}=2.3$ MW . . . . .	123
3.8	Expected unserved power to the system with wind speed = 12 m/s, $P_{WTG}=0.5$ MW and $P_{DG}=2.3$ MW . . . . .	124
3.9	EUP with wind speed = 6 m/s, $P_{WTG}=0.0852$ MW and $P_{DG}=7.1$ MW . .	128
3.10	EUP with wind speed = 9 m/s, $P_{WTG}=0.5652$ MW and $P_{DG}=7.1$ MW . .	129
3.11	EUP with wind speed = 13 m/s, $P_{WTG}=1.5$ MW and $P_{DG}=7.1$ MW . . . .	130
A.1	Look up table for conductors . . . . .	219
A.2	Look up table for transformer . . . . .	220
A.3	Input data of 15-bus radial distribution system . . . . .	220
A.4	Input data for 18-bus radial distribution system . . . . .	221
A.5	Input data of 33-bus radial distribution system . . . . .	222
A.6	5-bus test system data . . . . .	223
A.7	Parameters of the Squirrel Cage Induction Machine . . . . .	223
A.8	Parameters of the doubly fed induction machine . . . . .	224

# List of Symbols

$Rel_{norm_p}$	Normalized benefit of reliability achieved in presence of <i>WTG</i> and when <i>DG</i> quantum is $p$ MW
$Rel_{norm_v}$	Normalized benefit of reliability achieved in presence of <i>WTG</i> at wind speed $v$ m/s and the <i>DG</i> quantum suggested by MCS
$\bar{E}$	Grid or reference voltage = 1.0 p.u
$\bar{V}_2$	Voltage at transformer secondary
$\bar{V}_3$	Voltage at the load bus
$\beta$	Turbine blade pitch angle in degrees
$\delta_j^t$	Voltage angle at bus $j$ at time $t$
$\delta_k^t$	Voltage angle at bus $k$ at time $t$
$\lambda$	Tip speed ratio
$\lambda_b$	Failure rate of branch $b$ in <i>failures/yr</i>
$\lambda_{nom}$	Nominal value of tip speed ratio
$\mu$	Mean of the normal density
$\omega_r$	Angular speed of rotor
$\omega_s$	Angular speed of stator

$\omega_{nom}$	Nominal speed of turbine
$\rho$	Air density in $Kg/m^3$
$\sigma$	Standard deviation of the normal density
$\theta_{jk}$	Angle of admittance between bus $j$ and bus $k$
$A$	Area swept by the turbine blades in $m^2$
$bk$	Branch number
$C_1 - C_6$	Constants of performance coefficient
$C_p$	Performance coefficient of the turbine
$C_{DG}$	Cost of power generated by the DG in $\$/MWh$
$C_{ENS,DG_p}$	Cost of $ENS$ in $\$$ when $DG$ of $p$ MW output and $WTG$ are present in the distribution system
$C_{ENS,DG_v}$	Cost of $ENS$ in $\$$ when $WTG$ operates at wind speed of $v$ m/s and DG operates with a quantum suggested by MCS
$C_{ENS,DG}$	Vector containing cost of $ENS$ for different quantum of $DG$ in presence of both $DG$ and $WTG$
$C_{ENS,NoDG_v}$	Cost of $ENS$ in $\$$ at wind speed of $v$ m/s and when $WTG$ is the only distributed resource in the system
$C_{ENS,NoDG}$	Cost of $ENS$ in $\$$ when $WTG$ is the only distributed resource in the system
$C_{ENS}$	Cost of Energy not supplied in $\$$
$C_{EP}$	Cost of energy purchased from grid and DG in $\$$
$C_{Grid}^t$	Cost of power supplied by the grid at time $t$ in $\$/MWh$

$C_{nw}$	Cost of the Network to be upgraded in \$
$C_{p,pu}$	Per unit value of performance coefficient
$C_{p,max}$	Maximum value of performance coefficient
$C_{req}$	Capacitance required required to improve the voltage sensitivity
$C_{tf}$	Cost of the transformer to be upgraded in \$
$delX_C$	Step change in capacitive reactance
$E\{benefit\}$	Expected value of cost benefit
$ENS_i$	$ENS$ when DG is placed at bus $i$
$ENS_i^t$	Energy not supplied at time $t$ when DG is placed at bus $i$ in $MWh/yr$
$FC_{DG}$	Fixed cost of the DG
$i$	Candidate location for DG
$I_B$	Branch current vector
$I_D$	Current drawn by the load
$I_G$	Current injected by the generator
$I_i$	Current injection at bus $i$
$I_L$	Load current vector
$I_l$	Current flowing through the distribution line from source to load
$I_r$	Current supplied by the rotor circuit of $DFIG$
$I_s$	Current supplied by the stator circuit of $DFIG$
$I_{bk}$	Current flowing through branch $bk$

$I_{j,k,max}$	Current capacity of the branch connected between bus $j$ and bus $k$
$I_{j,k}$	Current flowing through the branch connected between bus $j$ and bus $k$
$I_{l,v_w}^{t(1)}$	Current flowing through the distribution line when wind speed is $v_w$ and transformer is operated at tap1
$I_{l,v_w}^{t(2)}$	Current flowing through the distribution line when wind speed is $v_w$ and transformer is operated at tap2
$j, k$	Bus numbers
$K_i$	Iterative count
$K_p$	Power gain
$K_w$	Wind speed count
$LC$	Load count indicating the number of loads to be restored by DG present in isolated system
$M$	Count used for Monte Carlo samples
$N$	Total number of buses in a given distribution system
$n$	Transformer turns ratio
$P_G$	Real power generated by the induction generator
$P_i$	Real power injected into bus $i$
$P_L$	Real power load at load bus
$P_m$	Output power of the wind turbine
$P_r$	Real power supplied by rotor of DFIG
$P_s$	Real power supplied by stator of DFIG

$P_T$	Net real power drawn by the load
$P_{ag}$	Air-gap power in the induction generator
$P_{D,peak}$	Peak load demand in the system
$P_{DG,max}$	Maximum real power that can be delivered by DG
$P_{DG,max}^t$	Maximum real power that can be delivered by DG at time $t$
$P_{DG,min}$	Minimum real power that can be delivered by DG
$P_{DG,net}$	Net power available in the isolated area due to distributed resources
$P_{DG,rem}$	Amount of power left after feeding the isolated priority load
$P_{DG_i}$	Real power delivered by DG placed at bus $i$
$P_{DG_i}^t$	Optimal real power delivered by DG placed at bus $i$ at time $t$
$P_{e,p.u}$	Per unit electrical power available at the rotor of the induction generator
$P_{ENS}$	Price of Energy not supplied in \$/MWh
$P_e$	Electrical equivalent of mechanical power available at the rotor of the induction machine
$P_{G,i}$	Real power generated by the induction generator placed at bus $i$
$P_{Grid_i}$	Real power drawn from the grid when DG is placed at bus $i$
$P_{Grid_i}^t$	Real power drawn from the grid at time $t$ when DG is placed at bus $i$
$P_{index}$	Index matrix containing information about the isolated load bus numbers
$P_{inj,i,j}$	Real power injection at bus $j$ when DG is placed at bus $i$
$P_{inj,i,j}^t$	Real power injection at bus $j$ at time $t$ when DG is placed at bus $i$

$P_{iso,load}$	Loads present in isolated portion of the system
$P_{L,i}$	Real power load at load bus when DG is placed at bus $i$
$P_{L,i,j}$	Real power load at load bus $j$ when DG is placed at bus $i$
$P_{load_j}$	Real power load at bus $j$
$P_{load_j}^t$	Real power load at bus $j$ at time $t$
$P_{m,pu}$	Per unit output power of the wind turbine
$P_{pr,iso,max}$	Maximum isolated priority load that can be restored
$P_{pr,iso}$	Isolated priority loads
$P_{pr,load}$	Priority loads in the entire system
$P_{rated}$	Rated capacity of WTG
$P_{sch,load}$	Load scheduled to DG when it is present in isolated system created by failure of branch $b$
$P_{ss,load}$	Real power load vector, whose each element represents sum of $LC$ loads taken at a time from an isolated system containing $n$ buses
$P_{ss,loss}$	Sub-system real power loss
$P_{WTG,min}$	Minimum real power that can be delivered by WTG
$P_{WTG}$	Real power delivered by WTG
$PI_{ENS_i}$	Performance Index of $ENS$ when DG is placed at bus $i$
$PI_{ENS_{norm,i}}$	Normalized Performance Index of $ENS$ when DG is placed at bus $i$
$PI_{TC_i}$	Performance Index of $TC$ when DG is placed at bus $i$
$PI_{TC_{norm,i}}$	Normalized Performance Index of $TC$ when DG is placed at bus $i$

$PI_{TPL_i}$	Performance Index of $TPL$ when DG is placed at bus $i$
$PI_{TPL_{norm,i}}$	Normalized Performance Index of $TPL$ when DG is placed at bus $i$
$pu$	Per unit
$Q_C$	Reactive power injected by the capacitor into the network
$Q_G$	Reactive power drawn by the induction generator
$Q_i$	Reactive power injected into bus $i$
$Q_L$	Reactive power load at load bus
$Q_s$	Reactive power supplied by stator of DFIG
$Q_T$	Reactive power drawn by the load
$Q_{Grid_i}$	Reactive power drawn from the grid when DG is placed at bus $i$
$Q_{Grid_i}^t$	Reactive power drawn from the grid at time $t$ when DG is placed at bus $i$
$Q_{inj_{i,j}}$	Reactive power injection at bus $j$ when DG is placed at bus $i$
$Q_{inj_{i,j}}^t$	Reactive power injection at bus $j$ at time $t$ when DG is placed at bus $i$
$Q_{L_{i,j}}$	Reactive power load at load bus $j$ when DG is placed at bus $i$
$Q_{load_j}$	Reactive power load at bus $j$
$Q_{load_j}^t$	Reactive power load at bus $j$ at time $t$
$R$	Radius to tip of the rotor
$r_g$	Gear ratio
$R_l$	Resistance of the distribution line
$R_r$	Rotor winding resistance

$R_s$	Stator winding resistance
$R_T$	Effective resistance offered for the flow of current from source to load end
$R_{bk}$	Resistance of branch $bk$
$r_{i,j,b}$	Supply restoration time of load connected at bus $j$ in <i>hours</i> when branch $b$ fails and DG is placed at bus $i$
$r_{i,j,b}^t$	Supply restoration time of load connected at bus $j$ in <i>hours</i> when branch $b$ fails and DG is placed at bus $i$ at time $t$
$RB$	Vector containing reliability benefit values obtained at different wind speeds
$RB_v$	Reliability benefit achieved in presence of <i>WTG</i> at wind speed $v$ m/s and the <i>DG</i> quantum suggested by MCS
$s$	slip
$S_i$	Complex power injected into bus $i$
$SC_{req}$	Feasible or switchable capacitance obtained by approximating $C_{req}$
$SL$	Vector containing isolated loads selected for supply restoration
$t$	Time in hours
$t(m)$	Transformer operating at tap $m$
$TC_i^t$	Total cost of power consumed by the system at time $t$ , when DG is placed at bus $i$ in \$
$TC_{DG_{i,q}}$	Total cost incurred in DSP by optimally sharing the load of $M^{th}$ Monte Carlo sample between grid, <i>WTG</i> and DG of $q$ MW capacity placed at bus $i$
$TC_{NoDG}$	Total cost incurred in DSP to satisfy the load of $M^{th}$ Monte Carlo sample through power supplied from grid and <i>WTG</i> in the distribution system

$TPL_i^t$	Total real power loss in the system at time $t$ , when DG is placed at bus $i$
$U_{i,j,b}$	Outage time of load connected at bus $j$ in <i>hours/yr</i> when branch $b$ fails and DG is placed at bus $i$
$U_{i,j,b}^t$	Outage time of load connected at bus $j$ in <i>hours/yr</i> when branch $b$ fails and DG is placed at bus $i$ at time $t$
$U_{i,j}$	Annual outage time of the load connected at bus $j$ in <i>hours/yr</i> when DG is placed at bus $i$
$U_{i,j}^t$	Annual outage time of the load connected at bus $j$ in <i>hours/yr</i> when DG is placed at bus $i$ at time $t$
$V_i, V_j, V_k$	Voltage magnitudes at buses $i, j$ and $k$ in pu
$V_j^t, V_k^t$	Voltages at bus $j, k$ at time $t$
$V_r$	Rotor voltage of <i>DFIG</i>
$v_r$	Rated speed of wind turbine in m/s
$V_s$	Stator voltage of <i>DFIG</i>
$v_w$	Wind speed in m/s
$V_{3,v_w}^{t(1)}$	Voltage at load bus when wind speed is $v_w$ and transformer is operated at tap1
$V_{3,v_w}^{t(2)}$	Voltage at load bus when wind speed is $v_w$ and transformer is operated at tap2
$V_{3,X_{tr1}}^{t(1)}$	Load voltage in the system with transformer having internal reactance $X_{tr1}$ and operating at tap1
$V_{3,X_{tr1}}^{t(2)}$	Load voltage in the system with transformer having internal reactance $X_{tr1}$ and operating at tap2

$V_{3,Xtr2}^{t(1)}$	Load voltage in the system with transformer having internal reactance $X_{tr2}$ and operating at tap1
$V_{3,Xtr2}^{t(2)}$	Load voltage in the system with transformer having internal reactance $X_{tr2}$ and operating at tap2
$V_{3i}$	Imaginary part of the voltage phasor $\bar{V}_3$
$V_{3r}$	Real part of the voltage phasor $\bar{V}_3$
$v_{ci}$	Cut-in speed of wind turbine in m/s
$v_{co}$	Cut-out speed of wind turbine in m/s
$v_{w,p.u}$	per unit wind speed
$v_{w,base}$	Base wind speed in m/s
$VD$	Voltage drop
$w_{r,gen}$	Angular speed of the wind generator rotor
$w_{r,turb}$	Angular speed of turbine rotor
$w_{s,gen}$	Angular speed of the wind generator stator
$x$	Random variable
$X_c$	Reactance of the capacitor connected at the load bus
$X_l$	Reactance of the distribution line
$X_m$	Magnetizing reactance
$X_r$	Rotor winding reactance
$X_s$	Stator winding reactance
$X_T$	Effective reactance offered for the flow of current from source to load end

$X_{C,req}$	Capacitive reactance required to improve the voltage sensitivity
$X_{tr}$	Internal reactance of the substation transformer
$Y_{jk}$	Admittance between bus $j$ and bus $k$

# Acronyms

<b>BIBC</b>	Bus-injection to branch-current
<b>DFIG</b>	Doubly fed induction generator
<b>DG</b>	Distributed generation
<b>DISCOM</b>	Distribution company
<b>DSO</b>	Distribution system operator
<b>DSP</b>	Distribution system planning
<b>EIL</b>	Expected value of isolated load
<b>ELR</b>	Expected value of load restored
<b>EMP</b>	Electricity market price
<b>ENS</b>	Energy not supplied
<b>EUP</b>	Expected unserved power
<b>GA</b>	Genetic algorithm
<b>LMP</b>	Locational marginal price
<b>LSA</b>	Loss sensitivity analysis
<b>MCS</b>	Monte Carlo Simulation

<b>MW</b>	Megawatt
<b>NMCS</b>	Total number of Monte Carlo samples
<b>pu</b>	per unit
<b>PDF</b>	Probability density function
<b>PI</b>	Performance Index
<b>RB</b>	Reliability benefit
<b>RWS</b>	Roulette wheel technique
<b>SCIG</b>	Squirrel cage induction generator
<b>STSA</b>	Spanning tree search algorithm
<b>TC</b>	Total cost
<b>TP</b>	Tap position
<b>TPL</b>	Total real power loss in the system
<b>TS</b>	Total number of MCS samples
<b>VSTC</b>	Voltage sensitivity to tap change
<b>WTG</b>	Wind turbine generator