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THE IMPACT OF DISTRIBUTED GENERATION ON DISTRIBUTION NETWORKS

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ABSTRACT

Distributed Generators (DG or embedded generators) are generators that are connected to the distribution network. Their advantages are the ability to reduce or postpone the need for investment in the transmission and distribution infrastructure when optimally located; the ability to reduce technical losses within the transmission and distribution networks as well as general improvement in power quality and system reliability. This paper highlights the benefits of distributed generation by using a 15-bus radial distribution network, modelled in the DIgSILENT Power Factory software, to demonstrate the improvement in voltage profile as well as the reduction in technical losses.

Keywords: *distributed generation; wind energy; integration of renewable sources and technical losses.*

1. INTRODUCTION

Distributed Generators (DG or embedded generators) are generators that are connected to the distribution network. Their advantages are the ability to reduce or postpone the need for investment in the transmission and distribution infrastructure when optimally located;the ability to reduce technical losses within the transmission and distribution networks as well asgeneral improvement in power quality and system reliability.

However, the development of renewable energy sources (e.g. wind or solar energy) and subsequent integration with the distribution network will increase the amount of generation so connected and this raises some technical issues such as [1]:

- inadvertent islanding where a section of a distribution network is to be split off the transmission network and is still energised by its embedded generators.
- the reversal of power flows which means that existing protection (if it is directional) cannot be used hence the need to install a new protection system.
- the connection of renewable generation can raise the fault levels due to the fault contributions from the renewable generators themselves to values beyond the capacity of existing switchgear. This will result in the installation of new circuit breakers which can be expensive. In order to ensure proper operation of power system protection schemes, it is necessary to provide proper and cost-efficient solutions for limiting the fault levels to their equipment capacity.
- Potential reactive power issues. This is because current wind generation technology, for example, has different electrical characteristics from conventional thermal, nuclear and hydro plants when large numbers of wind generators are installed on the network. The use of induction generators in place of the traditional synchronized generators will deliver a significant increase in reactive power and it is important that this is properly managed by the network operators. The increased reactive power on the network may prevent the connection of further wind generators to the network unless active steps are taken to absorb the reactive power.
- Fault Ride-Through Capabilities - As the penetration of renewable generation such as wind energy increases, the need to address the fault ride-through capability issues will become more critical. Hitherto, the wind turbines were allowed to trip when a

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voltage dip occurs. The wind turbines will now be expected to remain connected to the grid both during and after a fault. Upon voltage recovery, the wind turbines are not expected to consume excessive reactive power when re-exciting the generator, as this may result in a further voltage dip. This subject has been addressed elsewhere in [1].

Despite these technical challenges, many countries are reducing the greenhouse emissions and increasing the proportion of new forms of electricity generation [2]; the United Nations General Assembly has declared 2014 – 2024 as the decade for sustainable energy. A recent report from the International Energy Agency [3] showed that the use of renewable energy grew strongest last year and now produces about 22% of the global consumption of electricity. The UK, for example, imports nearly 50% of the coal it uses and it is also looking for new sustainable energy solutions for the future. Renewables will help avoid dependence on imports and make the country less vulnerable to security threats. The electricity generation via renewables increased by 27% during June 2011 and June 2012 to 38 TWh [4]. By 2020 UK hopes to provide 15% of its energy consumption from renewable sources.

Japan is the world's third largest economy and its energy policy is now centered on renewablesbecause these sources are regenerative and for practical purposes cannot be depleted. Hitherto Germany relied on nuclear power for 23% of its energy. However, as a result of the Fukushima incident and following mass anti-nuclear protests across Germany, the government announced a reversal of policy that will see all of their nuclear plants phased out by 2022. Germany is now basing its energy policy not on nuclear but on renewables.According to Belgovic (2011) in [5], the growth in renewables in the first quarter of 2011 in the USA was 25.82% whereas the growth of solar energy in 2011 was 104.8%.

South Africa has set a target of 10,000 GWh for renewable energy whereas the Government of Kenya is working with the International Renewable Energy Agency to explore its potentials in this area [3]. In Nigeria, the Ministry of Power [6,7] have identified the continued development of renewables and its integration to the grid as part of its future strategy.

Against this background, the objectives of this paper are to highlight the benefits of distributed generation by using a 15-bus radial distribution network, modelled in theDIgSILENT Power Factory software,todemonstrate the improvement in voltage profile as well as the reduction in technical losses. The modelling is presented in the next Section whereas the results are discussed in Section 3.

It is pertinent to mention that losses can be classified as technical or non-technical losses (comprising of illegal connections of electricity, metering errors and deficiencies, billing and processing errors etc); the subject of non-technical losses have been discussed elsewhere in [10] by Nwodo and Ekwue (1992).

2. TEST SYSTEM MODELLED IN DIGSILENT POWER FACTORY SOFTWARE

2.1 DIgSILENT Power Factory software

DIgSILENT[1] is a private company, headquartered in Gomaringen near Stuttgart, Germany and provides power system analysis software and related consultancy services. PowerFactory is its principal software offering, and is a wide-ranging PC based power system analysis package.

PowerFactory is suited to industrial, transmission and distribution networks, power plants as well as marine and aerospace industries. It was developed in Germany where it has been used very successfully, especially with the modelling of wind farms (their Doubly-Fed Induction Generator model was one of the first to be produced, and has been refined since)[12].

PowerFactoryhas the following capabilities[12]: balanced and unbalanced power flow; short circuit based on IEC 60909, VDE 0102/0103, ANSI C37 standards; transient stability; optimal power flow; low voltage network analysis etc. The software is suitable for this Study because:

- ithas the ability to analyse the impact of distributed generation on the network, and its generator models include induction machines, doubly-fed induction generators, fuel cells, micro-turbines, PV-cells, wind turbines, battery storage and single-phase machines.
- it is suitable for radial distribution networks. In radial distribution networks, the Jacobian matrix of the load flow equationsis usually ill-conditioned as a result of lack of diagonal dominance due to the high R/X ratio of distribution lines.

2.2 Radial Distribution Network

A 15-node radial distribution network sourced fromreference [8] was modelledin the DIgSILENT Power Factory software as shown in Figure 1. Table 1

[1] http://www.digsilent.de/

represents the bus data whereas the line data is embedded in Table 3 below. Table 2 shows the assumptions made for the DIgSILENT model.

Table 1: Nodal Data [8]

Node No	Load (kW + jkVAr)
2, 5, 10, 12	44.10 + j 44.99
3,7, 9,11, 15	70.00 + j 71.41
4, 6, 8, 13 , 14	140 + j 142.82

Table 2: Assumptions made in DIgSILENT Power Factory software

Parameter/System	Assumptions
Distribution line	Ground laying
Length of line	1 kilometre for each branch
Line model	Lumped parameter (Pi)
Load type	Constant power
Nominal frequency	50 Hz
System type	3-phase AC
Rated voltage	12 kV
Nominal voltage	11 kV
Voltage limits	Upper limit – 1.055 per unit Lower limit – 0.95 per unit
Bus 1	Slack or reference bus

The total system calculation report before the installation of the DG is shown in Figure 2.

Some of the methods of integrating wind energy to a network have been described in [9] as:

- use of classical squirrel cage induction wind turbine generators (WTG).
- use of induction WTGs with dynamic slip control.
- induction or synchronous WTGs connected through power electronic converters.
- Doubly Fed Induction Generators (DFIG).

A synchronous generator representing a modern off-shore wind turbine (as a DG) was modelled in DIgSILENT Power Factory software(Figure 3) and placed separately on buses 2 and 4 to investigate the impact of losses.The choice of these buses is arbitrary hence the authors have identified the need for further studies to account for the optimal allocation of DG. The wind turbine is assumed to generate 60% active power and 40% of reactive power.

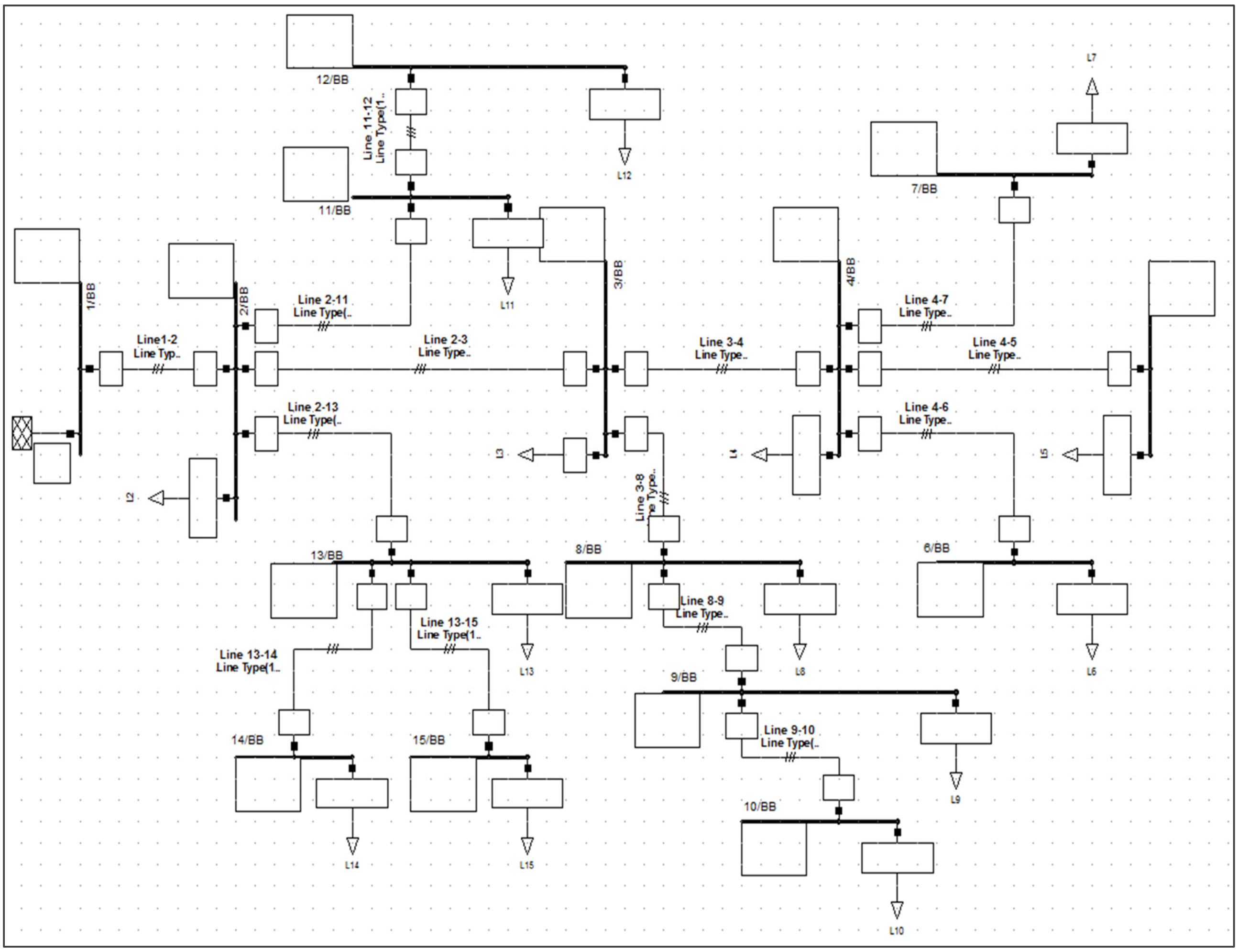

Figure 1: 15-node modelled in DIgSILENT Power Factory software

From Figure 2, with an external infeed of 1.29 MW, 1.31 MVar, the Active power of the DG = 60 percent of 1.29 MW = 0.774 MW

Reactive power of the DG = 40 percent of 1.31 MVAr = 0.524 MVAr

Under practical situations, the wind plant manufacturer will provide the P-Q diagram of the generator at the point of coupling with the distribution network. It must be ensured that the wind turbine generator is equipped with adequate reactive power capability to achieve appropriate reactive power regulation. The assumption above, in the absence of the appropriate P-Q diagram, is to ensure that sufficient reactive power is available to ensure satisfactory operation of the wind turbine generator.

With a nominal voltage of 11kV and assumed power factor of 0.9, the nominal apparent power of the DG can be calculated as:

$$Apparent\ Power(S) = \frac{Active\ Power}{Power\ factor} = \frac{0.774}{0.9}$$

$$= 0.86\ \text{MVA} \qquad (1)$$

With the apparent power of 0.86 MVA, it was found that the synchronous generator was overloaded hence the value of 1 MVA was chosen instead. Other parameters were left at default values as shown in Figure 4.

Under practical purposes an optimal allocation of DG, taking into account physical constraints such as available capacity, costs, location and size etc will be carried out first to determine the appropriate buses; this is the subject of further research. Also the default values of the synchronous generator as set in the software were used and no attempt was made to fine tune the control parameters.The dynamic interaction between the wind turbine generator and the distribution network was not modelled as the main interest in this paper is the steady state operation.

```
| DIgSILENT PowerFactory 15.0.3 | Project:
|                               | Date:  9/5/2014

| Load Flow Calculation                                              Total System Summary |

   AC Load Flow, balanced, positive sequence        | Automatic Model Adaptation for Convergence    No
   Automatic Tap Adjust of Transformers       No    | Max. Acceptable Load Flow Error for
   Consider Reactive Power Limits             No    |   Nodes                                       1.00 kVA
                                                    |   Model Equations                             0.10 %

| Total System Summary                  | Study Case: Study Case              | Annex:          / 1 |

 No. of Substations    15       No. of Busbars      15      No. of Terminals     186     No. of Lines           14
 No. of 2-w Trfs.      0        No. of 3-w Trfs.    0       No. of syn. Machines 0       No. of asyn.Machines   0
 No. of Loads          14       No. of Shunts       0       No. of SVS           0

 Generation            =      0.00  MW          0.00  Mvar      0.00  MVA
 External Infeed       =      1.29  MW          1.31  Mvar      1.83  MVA
 Load P(U)             =      1.22  MW          1.25  Mvar      1.75  MVA
 Load P(Un)            =      1.23  MW          1.25  Mvar      1.75  MVA
 Load P(Un-U)          =      0.00  MW          0.00  Mvar
 Motor Load            =      0.00  MW          0.00  Mvar      0.00  MVA
 Grid Losses           =      0.06  MW          0.06  Mvar
 Line Charging         =                        0.00  Mvar
 Compensation ind.     =                        0.00  Mvar
 Compensation cap.     =                        0.00  Mvar

 Installed Capacity    =      0.00  MW
 Spinning Reserve      =      0.00  MW

 Total Power Factor:
   Generation          =        0.00  [-]
   Load/Motor          =  0.70 / 0.00  [-]
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Figure 2: Total system calculation report before the introduction of DG

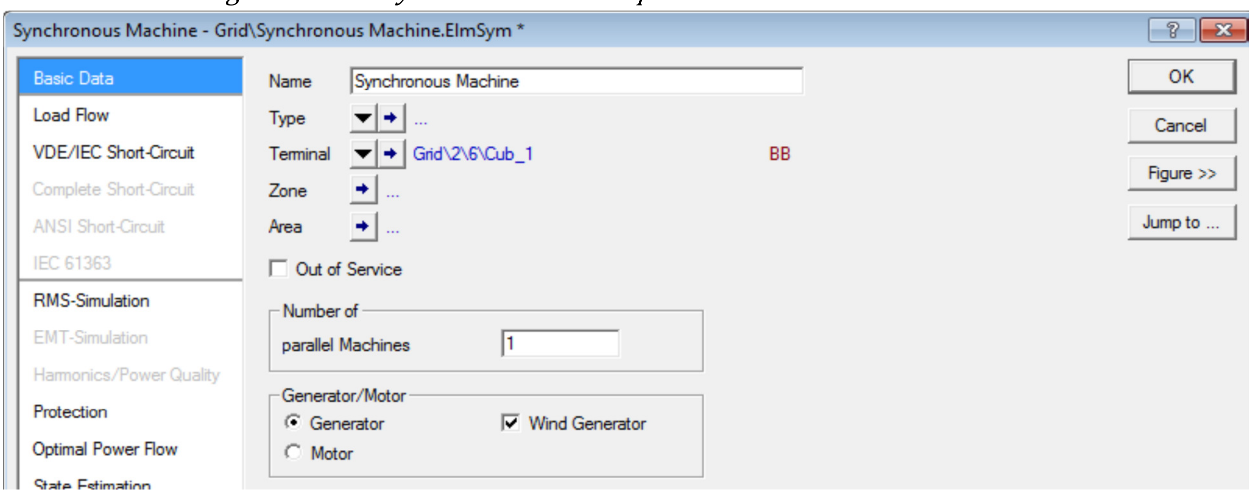

Figure 3: Synchronous Machine Basic Data

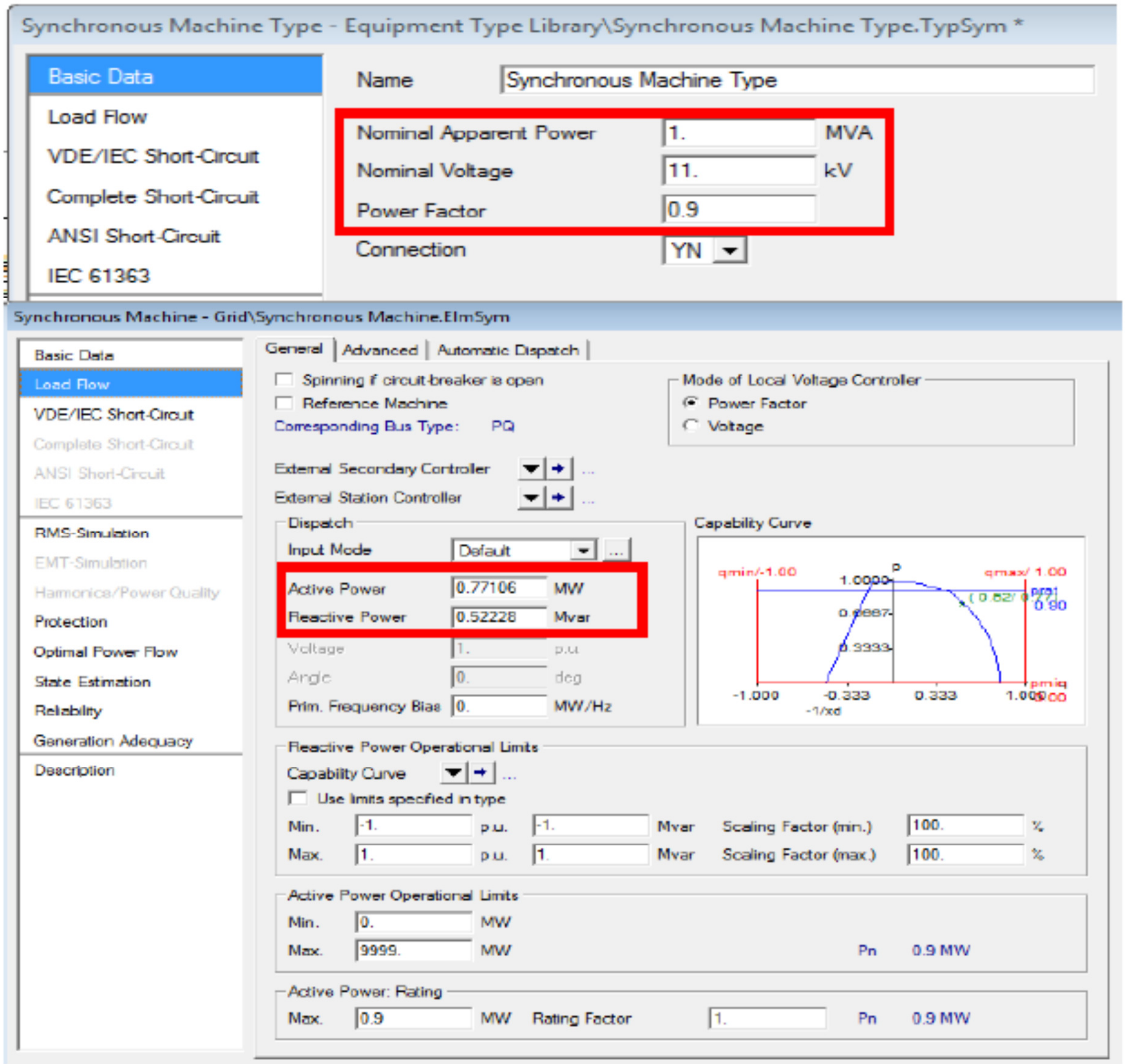

Figure 4: Synchronous Machine Data

3. RESULTS

3.1 Reduction in Technical Losses

Losses can be classified as technical or non-technical losses (comprising of illegal connections of electricity, metering errors and deficiencies, billing and processing errors etc) as shown in Figure 5. The combined losses could be up to 30% or more particularly in developing countries and this requires a major high level intervention. It has been shown in [2], using the transmission and distribution losses (% of output) data compiled by the World Bank from 1971 to 2011 for some arbitrarily chosen developed and developing countries, that for most developed countries the technical losses are between 4% and 10%. The subject of non-technical losses have been discussed elsewhere in [10] by Nwodo and Ekwue in 1992.

The results achieved by having no DG, placing the DG at either bus 2 or 4 are shown in Table 3.

$$\text{The line losses} = 3 \times I^2R \qquad (2)$$

where I is the current and R the resistance of the line. The initial losses shown in Figure 2 as 0.06 MW from the load flow result has been validated in Table 3.

The technical losses have reduced from 0.06MW with no DG to 0.03 MW when the DG was placed at bus 2 (i.e. 50% reduction) and to 0.02 MW when placed on bus 4 (i.e. 67% reduction).

Further minimization of technical losses can be achieved by controlling the switchable reactive power sources, generator terminal voltages, transformer tap ratios and phase-shifters using a technique proposed in [13].

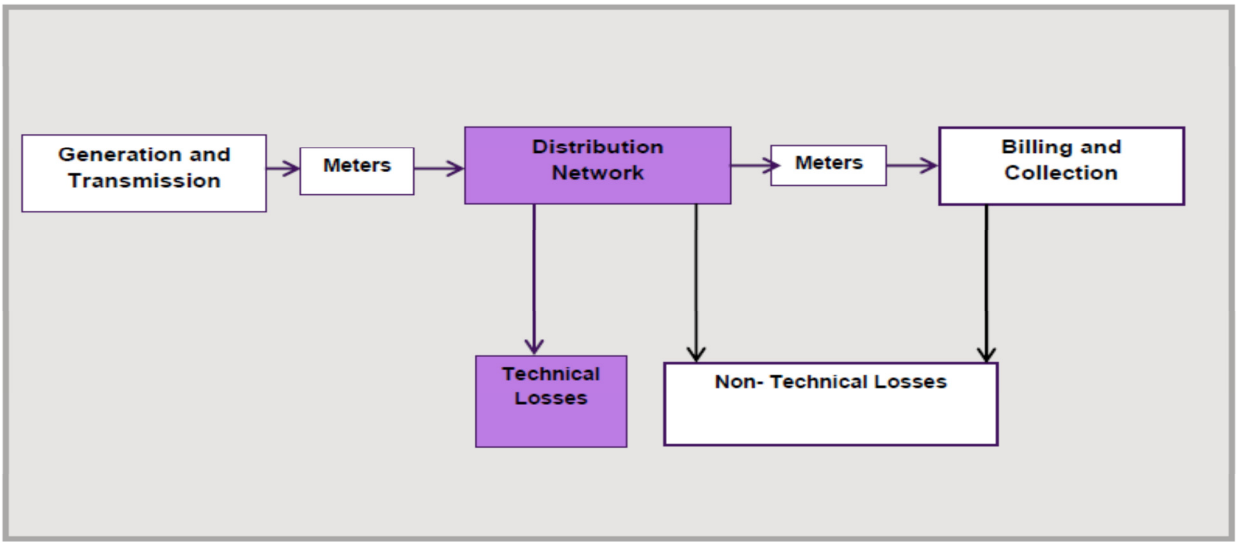

Figure 5: Typical Classification of Losses in a Distribution Network

Table 3: Comparison of line currents and technical losses with no DG, DG at bus 2 and DG at bus 4

				Before DG		After DG inserted in bus 2		After DG inserted in bus 4	
Sending node	Receiving node	R (ohms)	X (ohms)	Current I (kA)	Technical Losses (MW)	Current I (kA)	Technical Losses (MW)	Current I (kA)	Technical Losses (MW)
1	2	1.35309	1.32349	0.096	0.03741	0.047	0.00897	0.046	0.00859
2	3	1.17024	1.14464	0.057	0.01141	0.056	0.01101	0.012	0.00051
3	4	0.84111	0.82271	0.031	0.00242	0.031	0.00242	0.021	0.00111
4	5	1.52348	1.0267	0.004	0.00007	0.003	0.00004	0.003	0.00004
4	6	1.19702	0.8074	0.011	0.00043	0.011	0.00043	0.011	0.00043
4	7	2.23081	1.5047	0.006	0.00024	0.005	0.00017	0.005	0.00017
3	8	1.79553	1.2111	0.02	0.00215	0.02	0.00215	0.02	0.00215
8	9	2.44845	1.6515	0.009	0.00059	0.009	0.00059	0.009	0.00059
9	10	2.01317	1.3579	0.004	0.00010	0.003	0.00005	0.003	0.00005
2	11	2.01317	1.3579	0.009	0.00049	0.009	0.00049	0.009	0.00049
11	12	1.68671	1.1377	0.003	0.00005	0.003	0.00005	0.003	0.00005
2	13	2.55727	1.7249	0.027	0.00559	0.027	0.00559	0.027	0.00559
13	14	1.0882	0.734	0.011	0.00040	0.011	0.00040	0.011	0.00040
13	15	1.25143	0.8441	0.006	0.00014	0.005	0.00009	0.005	0.00009
Total					0.06149		0.03246		0.02027

3.2 Improvement in Voltage Profile

Before the introduction of distributed generation, lower voltages (i.e. below the stated 0.95 pu minimum value stipulated) were noted at buses 6, 7, 9 and 10. Bus 10 had the lowest voltage because it is farthest from the source (i.e. bus 1).

The voltages improved as the DG was inserted in bus 2 and then bus 4 as shown in Table 3. More system studies and results are available in [11] by Akintunde.

4. CONCLUSIONS

This paper has highlighted the benefits of distributed generation by using a 15-bus radial distribution network, modelled in the DIgSILENT Power Factory software, todemonstrate the improvement in voltage profile as well as the reduction in technical losses. Fixed (or no load, shunt or iron) losses as a result of hysteresis and eddy current losses in the iron core of transformers have not been included in this model. They are usually treated as constant and independent of network loading. Though only wind energy, as an example of a renewable source, was considered in this paper, similar conclusions will be reached by using other forms of renewable energy such as solar, biomass, geothermal etc.

Table 3: Comparison of bus voltages with no DG, DG at bus 2 and DG at bus 4

Bus	Before DG	After DG inserted in bus 2	After DG inserted in bus 4
1	1	1	1
2	0.971	0.986	0.987
3	0.957	0.972	0.985
4	0.951	0.966	0.988
5	0.95	0.965	0.987
6	0.949	0.964	0.986
7	0.949	0.964	0.986
8	0.95	0.965	0.978
9	0.946	0.961	0.974
10	0.945	0.96	0.973
11	0.968	0.983	0.983
12	0.967	0.982	0.982
13	0.958	0.973	0.974
14	0.956	0.971	0.971
15	0.957	0.972	0.972

The work described in this paper fits in with the Nigeria's Ministry of Power strategy of continued development of renewable energy sources and addressing high energy losses in the transmission and distribution networks.Future investigations will address the optimum allocation of DG taking into account physical constraints (such as cost, location etc) to reduce technical losses and improve on voltage profiles as well as the dynamic interaction between the wind turbine generator and the distribution network.

5. ACKNOWLEDGEMENT

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