Power Quality Analysis of Electrical Distribution Systems with Asynchronous Generators

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Abstract- In recent times, it has been observed that the implementation of efficient Distribution Systems are the back bone of smart grids. Further, the need of the hour is to realize a more flexible system involving energy savings and encouraging environmental factors leading to development of Distributed Generation Systems (DGs), which are expected to play an important role in efficient operation. In this context, efforts are made to determine the effect of DGs on the electrical distribution networks. Different electrical configurations of asynchronous generator - wind turbines have been considered leading to an algorithm developed to determine the influence of optimally placed DGs at various buses in the system. The system is analyzed through different Power Quality Indices (PQIs), which are calculated by applying probability concepts, that overcome the limitations associated with traditional methods of calculations. Additionally, a new PQI based on Total Demand Distortion (TDD) is also presented. An intelligent control algorithm based on machine learning concepts is incorporated, enabling to initiate power quality improvement/control strategies to be adopted by the distribution manager. A 17-bus test system is considered and modelled using Open Distribution System Simulator (OpenDSS). The results obtained are analyzed by MatLab - OpenDSS Component Object Model (COM) interface. The efficacy of the results is imminent based on a comparison with similar results obtained by the authors in the related literature.

Keywords Electrical Distribution System, Distributed Generation, Smart Grid, Power Quality, Harmonics.

1. Introduction

In flexible Electrical Power systems (EPS), Distributed Generation systems (DGs) are considered as a subset of distributed resources connected to a system area through a point of common coupling [1]. Wind, Solar Photovoltaic, Diesel Generator, etc. are some of the examples for such generations. Of the many forms of DGs used in practice, the use of Asynchronous Generator with wind turbine, in different configurations, has been widely preferred. There are four types of electrical configurations of Asynchronous Generator-wind turbine: Fixed-Speed Wind Turbine (FSWT) - also known as Squirrel cage Induction Generator (SCIG), Wide-Slip Wind Turbine (WSWT), Doubly-Fed Induction Generator (DFIG) wind turbine, and full converter wind turbine [2-3].

In general, DGs provide voltage support, reduce losses and improve Power Quality (PQ) of the system. However, wind power generators inject power into the grid, resulting in voltage rise/sag/swell/fluctuations. Thus, it is probable that, depending on their configuration, DGs introduce disturbances that may result in reduction of PQ [4–12]. For example, in case of wind turbine equipped with PE converter, harmonics are injected into the system by the converters [13]. Hence, the assessment of PQ level is required for studies connected with the smart distribution systems involving DGs. The assessment can be carried out in two stages: PQ assessment before DG installation and PQ assessment after the installation of DG, requiring different tools and quantities, with the scope of these assessment methods being different.

The PQ assessment before DG installation are carried out based on optimization algorithms to find the optimal location and size of DG units, which are generally incorporated during planning stage [14–16]. However, it is found to be necessary to verify the effectiveness of the PQ assessment algorithms, even after the installation of DGs. In this research work, the analysis of Electrical Distribution Systems (EDS) from PQ perspective is presented through a selected sample-test system. Once the DGs are optimally placed, variations of PQ levels are monitored. For all the cases of deviations observed with reference to maintenance of improved power quality, proper control actions are initiated. A machine learning algorithm based on Least Square Support Vector Machine concept has been used for facilitating the control actions. The system is modeled and analyzed through OpenDSS-MatLab COM interface [17]. The novelty of the results is found to be in the PQ analysis using intelligent algorithms corresponding to the post-DG-installation period.

2. Methodology

In this section, the concepts of probability for PQ study and calculation of various Power Quality Indices (PQIs) for PQ assessment before and after the installation of DGs have been discussed. Implementation of the algorithm to arrive at various PQIs and their effectiveness after the installation of DGs for selected test system are presented.

2.1. Probability concepts as applied to THD calculations

The concepts such as Fast Fourier Transform, Short Time Fourier Transform and Discrete Fourier Transform based on Fourier Transform (FT) have crept into power quality analysis. However, there are certain limitations of FT based analysis. Such as, the trend of harmonics induced by a particular electrical load is dynamic in nature, where as the limits of Total Harmonic Distortion (THD) are steady state limits [18]. To overcome limitations of FT, probability plots are developed from recorded voluminous data that are compressed and represented precisely [19-20]. In this context, the PQ variations are monitored continuously and the data's are recorded, which are later processed to obtain PQIs.

2.2. Mathematical Modeling

Different PQIs useful for quantification of distribution system behavior are reported in [21-22]. The harmonics associated PQ attributes: THD and Total Demand Distortion (TDD), corresponding to either a single bus-**i** or for the whole system (**S**), can be characterized by an index, x, in terms of either the bus-current (**I**) or bus-voltages (**V**). In general, for a given n- bus system, the PQ index, x_i, at the bus-i, when expressed in normalized form, in terms of the index values corresponding to the pre-installation and post -installation stages of DG, is given by:

$$x_i = \frac{x_i - x_{i_{DG}}}{x_i} \quad \forall i=1 \text{ to } n \tag{1}$$

where, this index can either be positive or negative, depending on the attribute considered. Accordingly, the various power quality indices considered for the proposed PQ assessment studies are defined [for x_i of (1)] as per the following equations:

$$\mathrm{THD95}_{\_V_i} = \frac{\mathrm{THD} - \mathrm{THD_{DG}}}{\mathrm{THD}} \times 100 \tag{2}$$

$$\mathrm{TDD95}_{\_I_i} = \frac{\mathrm{TDD} - \mathrm{TDD_{DG}}}{\mathrm{TDD}} \times 100 \tag{3}$$

$$\mathbf{S}\mathrm{THD95\_V} = \frac{\mathrm{STHD} - \mathrm{STHD_{DG}}}{\mathrm{STHD}} \times 100 \tag{4}$$

$$\mathbf{S}\mathrm{TDD95\_I} = \frac{\mathrm{STDD} - \mathrm{STDD_{DG}}}{\mathrm{STDD}} \times 100 \tag{5}$$

$$\mathbf{SA}\mathrm{THD\_V} = \frac{\mathrm{SATHD} - \mathrm{SATHD_{DG}}}{\mathrm{SATHD}} \times 100 \tag{6}$$

$$\mathbf{SAE}\mathrm{THD\_}\mathbf{V} = \frac{\mathrm{SAETHD} - \mathrm{SAETHD_{DG}}}{\mathrm{SAETHD}} \times 100 \tag{7}$$

Here, the prefixes S, SA and SAE respectively correspond to the System, System Average and System Average Excessive indices, while the suffixes, V and I correspond to the expressions in terms of bus voltages and bus currents only. Thus, the equations (2-3) give the *site indices* relative to bus-i, whereas equations (4-7) give the *system index* corresponding to the complete system. The number 95 used in the PQ indices defined above refers to the 95th percentile Cumulative Probability (CP) value of distribution, which is better than the maximum value, being less sensitive to spurious measurements [23]. For instance, when a system's THD is monitored, STHD corresponds to the value of THD which is less than system's THD in 95% of the measurements. It is thus evident that the remaining 5% of measurements would have a THD that is higher than the STHD value. Here, the calculations of various indices are done as per the fundamental equations defining the THD and TDD. For example, some of the indices above are obtained first as per the relation:

$$\mathrm{STHD} = \frac{\sum_{s=1}^{n} L_s \times CP95(THD_s)}{\mathrm{L_t}} \tag{8}$$

$$\mathrm{SATHD} = \frac{\sum_{s=1}^{n} \mathrm{L_s} \times \mu \times (THD_s)}{\mathrm{L_t}} \tag{9}$$

$$\mathrm{SAETHD} = \frac{\sum_{s=1}^{n} \mathrm{L_s} \times \frac{\mathrm{N_{THD}}}{\mathrm{N_{tot}}}}{\mathrm{L_t}} \tag{10}$$

where:

s = circuit segment number

THDs = THD of circuit segment s corresponding to 95th percentile of the measurement

N_{THD} = number of steady state measurements that exhibit a THD value for segment s which exceeds the specified THD threshold value

N_{tot} = total number of steady state measurements recorded for segment 's' over the assessment period.

L_S=connected KVA served from circuit segment s

L_t= Total KVA served from the system

$CP95_S$=95th % cumulative probability value

2.3. Implementation

An example distribution system including DGs, as shown in Fig. 1 is considered for analysis [24]. By using all the relevant data available in literature with respect to the selected system, the load flow analysis is carried out using the OpenDSS software tool.

The methodology adopted for the proposed work is shown in Fig. 2. All the available run-options of the load flow algorithm are made use of during the simulation process, which include: different solution modes, load variations, wind power generator time schedules, etc.. These load flow results are further used to run the harmonic power flow, as per a predetermined harmonic spectrum obtained with a six- pulse converter simulated through a MatLab platform. Here, the converter is adapted as a substitute to the non-linear load & DFIG converter. The results of harmonic analysis are used to verify deviations, if any, in $THD95_{\_V_i}$, $STDD95_{\_I_i}$, etc., at each of the bus and the system as a whole, by way of calculating the various PQIs as per equations (2) to (9), presented in section 2.2.

The objective is to realize an overall improvement in system PQ. Till such time, a series of machine learning based control actions are initiated by the operator through a decision manger, as depicted in the flow diagram of Fig. 2. These control actions are initiated based on processing of signals by using S-Transform, extracting the features and then feeding to the machine learning algorithm [25]. Suitable time-domain to frequency-domain and vice-versa analysis have been carried out while extracting the data from the monitors, processing them and initiating control actions. The proposed analysis is carried out once again with the newer control actions incorporated and verified for possible deviations in PQ parameters. This is iteratively repeated, till such time that all the PQIs correspond to an improved PQ of the system. As a further step in this direction, the study and application of S-transform and LSSVM technique for initiating control actions, have also been carried out and the corresponding results have been successfully submitted as a research article/paper at IEEE PEDES conference [26].

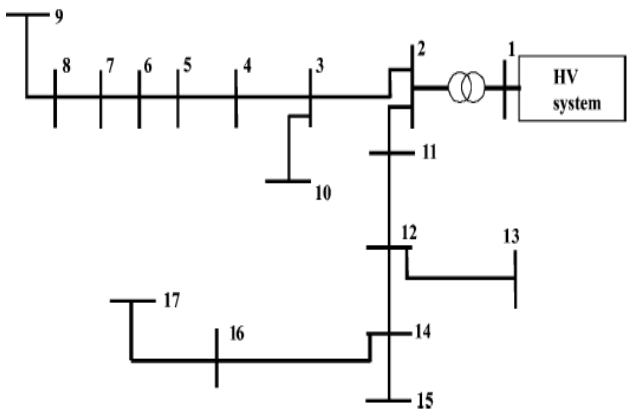

Fig. 1. Sample test System.

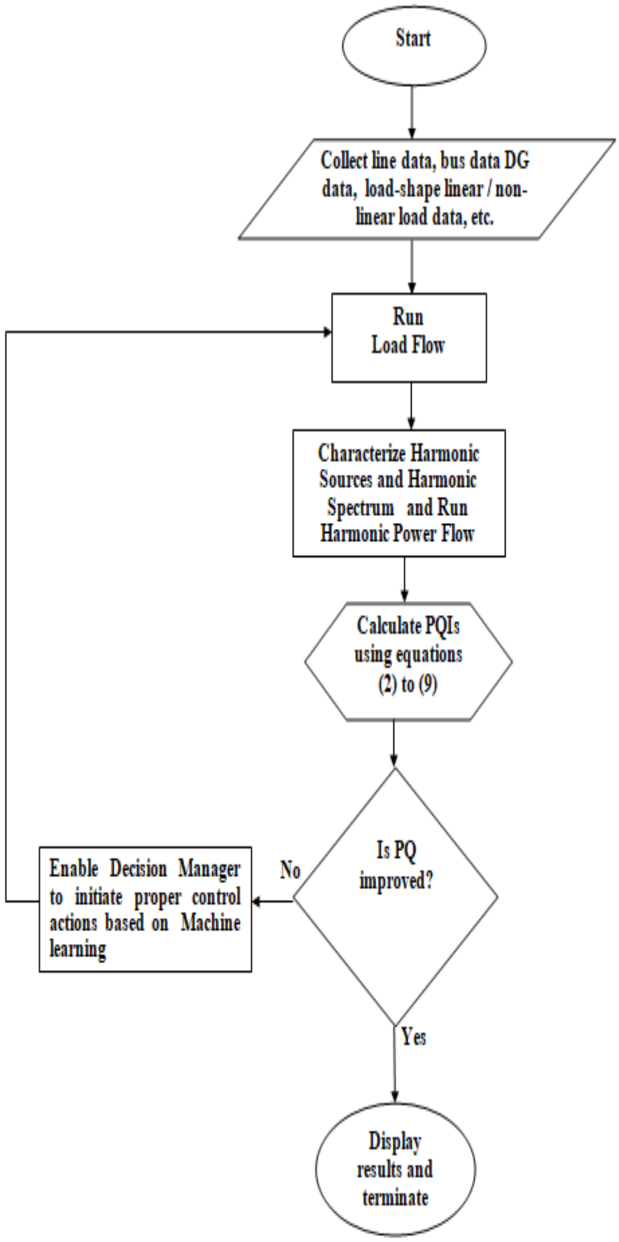

Fig. 2. Methodology adopted.

3. Results & Discussion

Effect of different types of DGs on the PQ levels are evaluated for the test system considered along with SCIG and DFIG type DGs. The results obtained are presented in this section.

3.1. Distribution network with SCIG type DGs

Since the objective of the proposed work is to verify the effectiveness of DGs on the distribution network w.r.t. various PQIs and their quantification, the size and location of DGs are selected based on available literature corresponding to the selected 17-bus test system. Accordingly, the studies have been conducted by varying the installation buses as 9, 12 & 17 respectively and sizes of DGs as 1.65 MW, 3.3 MW and 4.95 MW. Various PQI are obtained as discussed in section 2. The CP95 percentile voltage at each bus in the absence and in the presence of 1.65 MW, 3.3 MW and 4.95 MW DG (SCIG) at buses 9,12 and 17 are presented in Fig. 3. The voltage profile of the system is improved as depicted in this plot. A comparative results of CP95 voltage at each buses during planning stage is presented in Table 1. It is observed that the overall voltage profile of the system increases with the increase in the size of the DG used.

Table 1. The 95th percentile of fundamental voltage at each bus before and after the installation of SCIG.

Bus No.	**V_f [p.u.]**			
	Without DG	***1.65 MW DG at bus-9***	***3.3 MW DG at bus-12***	***4.95 MW DG at bus-17***
1	1.05	1.05	1.05	1.05
2	1.0425	1.0419	1.0412	1.0403
3	1.0317	1.0311	1.0304	1.0295
4	1.0172	1.0164	1.0158	1.0149
5	1.0098	1.0088	1.0083	1.0074
6	0.9917	0.9903	0.9902	0.9893
7	0.9907	0.9892	0.9892	0.9883
8	0.9884	0.9881	0.9870	0.9860
9	0.9842	0.9883	0.9827	0.9818
10	1.0312	1.0305	1.0298	1.0289
11	1.0213	1.0207	1.0242	1.0247
12	1.0078	1.0072	1.0138	1.0154
13	1.0078	1.0071	1.0138	1.0154
14	0.9840	0.98334	0.9901	0.9992
15	0.9828	0.98219	0.9890	0.9981
16	0.9666	0.96601	0.9729	0.9996
17	0.9665	0.9658	0.9727	1.018

The THD 95th percentile variation with DG (3.3 MW) at specific locations are shown in Fig. 4. When SCIG is connected at different buses, the values obtained are positive, indicating that, there is improvement in harmonic distortion. Table 2 shows the PQIs obtained at the planning stage. The required indices: STHD95_V, SATHD_V and SEATHD_V are calculated with the location and sizes considered as per the base reference article [24], and the results are in agreement. Table 2 also shows a comparative study of results obtained vis-a-vis the results presented in [24], wherein it is observed that, the results trend remains the same, although, there is an expected wide deviation in certain minimial cases, which could be largely due to the various operational parameters assummed by the authors in [24]. As a further analysis, results of PQ indices are also obtained for STDD95_I by calculating TDD with the location and sizes unchanged. From the analysis of results presented in Table 2, it is apparent that in all the cases considered (except for the case of bus #9 with 3.3 MW DG, which is, in any way, not considered for further analysis), when SCIGs are connected to the system, there is improvement, as most of the values reported are positive, indicating reduction in harmonic distortion.

It is also inferred that, at bus 17, the highest improvements are realized irrespective of the size of the DG. In this context, to validate the efficacy of the proposed method, the system is simulated by considering installation bus as 17, with variations in load. The results so obtained are presented in Table 3. It may be noted that, the indices given in Table 3 are obtained with new system conditions (change in load, wind speed, etc.). These values are in close agreement with the benchmark data available in literature [23]. Further, improvement in PQ for all the cases considered is observed, as presented in Table 3. Thus, no control actions are suggested for such cases.

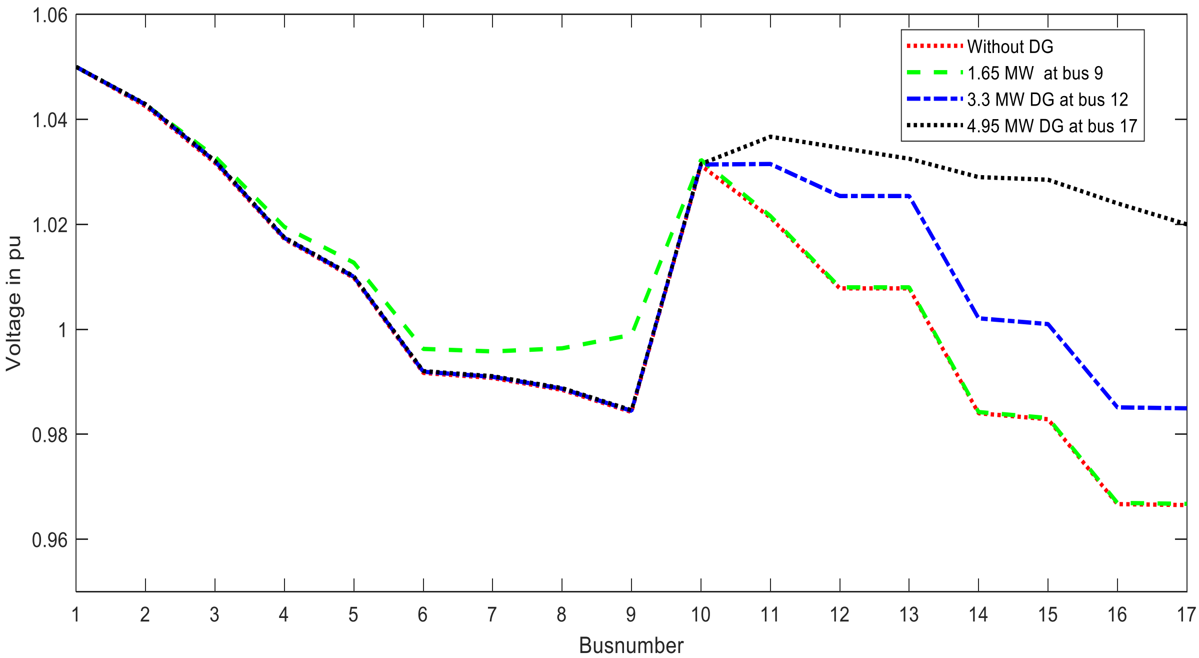

Fig. 3. 95th percentile bus-voltages without and with SCIG at specific locations.

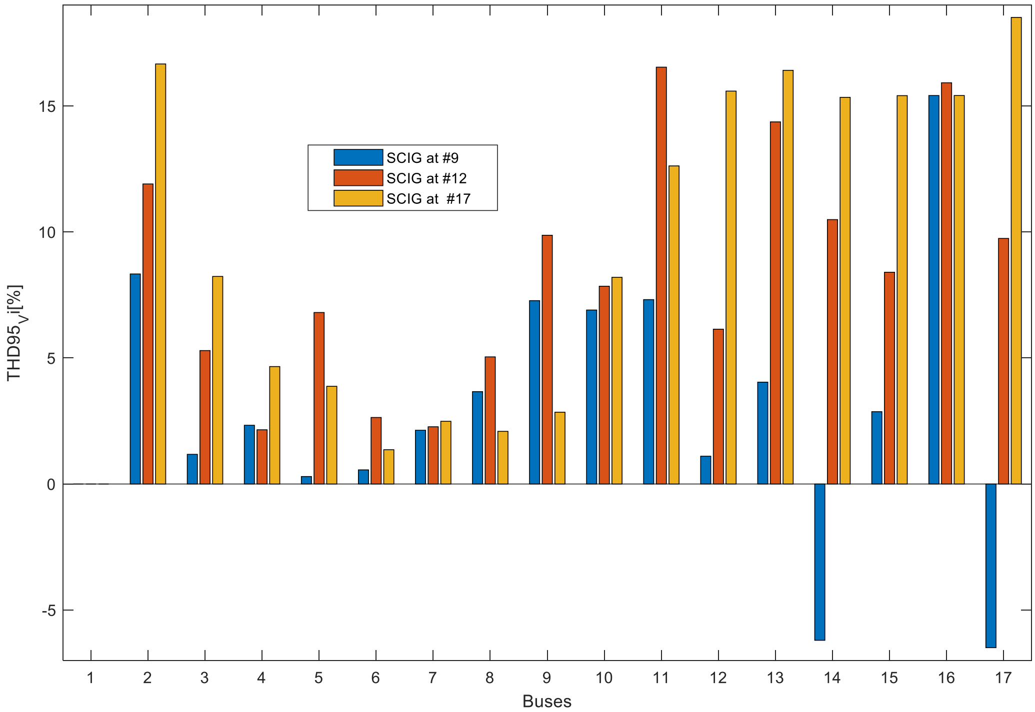

Fig. 4. THD 95th percentile variation with SCIG (3.3 MW) at specific locations.

Table 2. PQIs before installation of SCIG type DGs (Planning stage)

Indices	**Methods Considered**	**DG Capacity= 1.65 MW**			**DG Capacity= 3.3 MW**			**DG Capacity= 4.95 MW**		
		DG location			**DG location**			**DG location**		
		#9	*#12*	*#17*	*#9*	*#12*	*#17*	*#9*	*#12*	*#17*
SATHD_V	Proposed Method	1.60	2.1	2.45	3.58	4.5	14.21	7.21	13.49	21.65
	Results as per [24]	3.85	5.42	7.21	6.64	10.48	15.51	9.84	15.62	22.64
STHD95_V	Proposed Method	3.007	4.8	2.1	-0.24	5.514	13.12	4.57	5.78	8.117
	Results as per [24]	1.58	5.14	1.42	-0.14	5.74	15.62	5.21	6.48	18.01
SEATHD_V	Proposed Method	0.012	0.045	0.175	0.28	0.49	1.75	0.74	2.74	10.21
	Results as per [24]	0.018	0.65	0.187	0.278	0.65	2.97	0.84	2.95	11.46
STDD95_I	Proposed Method	0.009	0.012	0.118	0.15	0.21	0.28	0.34	0.57	0.89

Table 3. Verification of effectiveness of PQIs after installation of SCIG

Indices (%)	**DG Location #17**			**Improve-ment in PQ**
	DG capacity (MW)			
	1.65	**3.3**	**4.95**	
$SATHD\_V_{DG}$	1.61	1.42	1.54	Yes
$STHD95\_V_{DG}$	4.34	4.12	3.98	

3.2. Distribution network with DFIG type DGs

The DFIG type DGs are generally interfaced to the electrical network through PE converters. Hence, they may affect the PQ of the system. In this context, for the same system, with the location and sizes of DGs unchanged, further analysis is carried out by placing DFIG. The CP95 percentile voltage at each bus in the absence and in the presence of 1.65 MW, 3.3 MW and 4.95 MW DFIG at buses 9,12 and 17 are presented in Fig. 5.

As the size of the DG increases, overall voltage profile of the system improves, as evident for the case of SCIG. The THD 95th percentile variation with DFIG (3.3 MW) at specific locations are shown in Fig. 6. It is evident that, as, PE converters of DFIG injects harmonics, the PQ indices obtained are negative, indicating increased level of harmonic distortion, as given in Table 4.

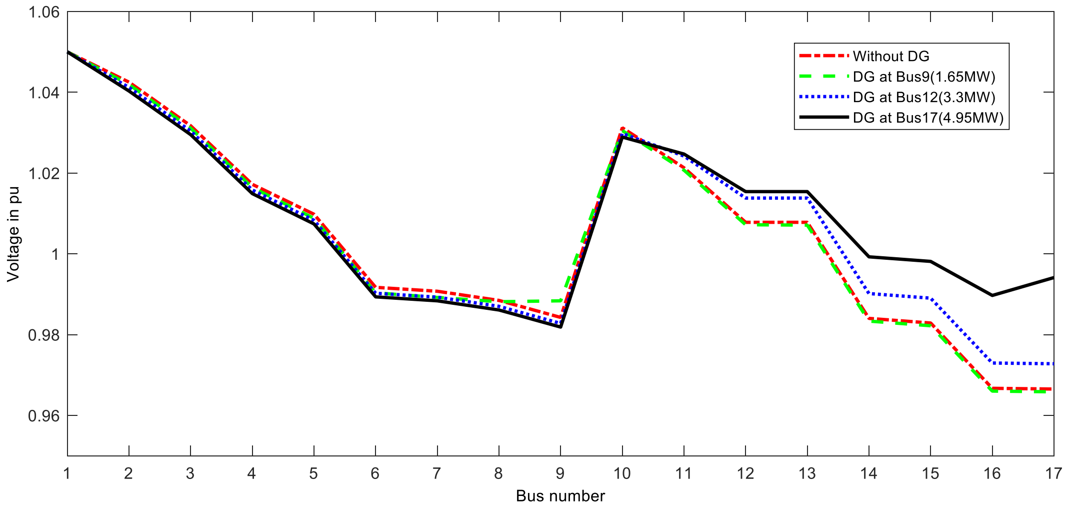

Fig. 5. 95th percentile bus-voltages without and with DFIG at specific locations.

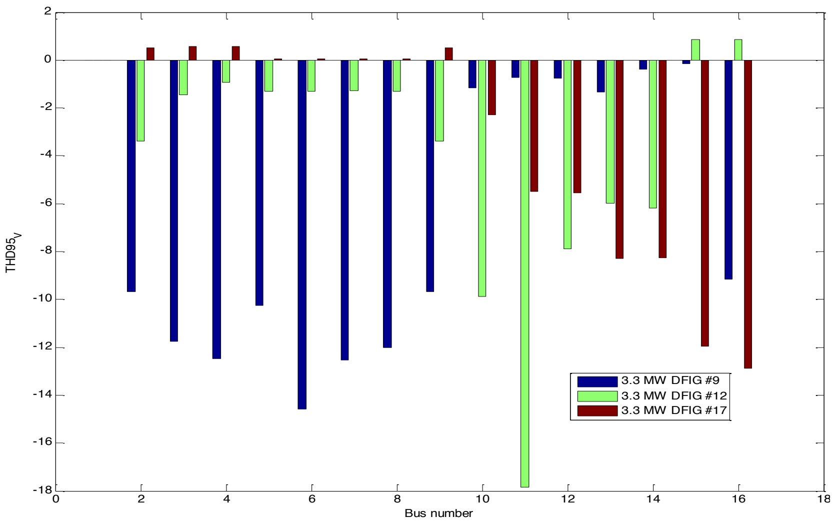

Fig. 6. THD 95th percentile variation without and with DFIG at specific locations.

Table 4. PQIs before installation of DFIG (Planning stage)

Indices (%)	**DG Capacity= 1.65 MW**			**DG Capacity= 3.3 MW**			**DG Capacity= 4.95 MW**		
	DG location			**DG location**			**DG location**		
	#9	*#12*	*#17*	*#9*	*#12*	*#17*	*#9*	*#12*	*#17*
SATHD95_V	-1.45	-2.1	-0.45	-2.14	-1.45	-0.21	-4.45	-3.49	-0.65
STHD95_V	-4.01	-2.98	-0.51	-0.24	-5.514	-1.27	-6.57	-5.78	-1.14
SEATHD_V	-0.187	-0.041	-0.0120	-0.81	-0.43	-2.1	-8.21	-3.34	-0.47
STDD95_I	-0.0014	-0.021	0.21	-0.45	-0.38	-0.19	-0.65	-0.87	-1.24

Further, to obtain the improvements in PQ levels, intelligent actions initiated. Two different load and wind patterns are considered to validate the results proposed. These results are presented in Table 5, as case-a and case-b. Bus-17 is considered as installtion bus with DG of 4.95 MW. Capacitors at various locations are considered [21], which are properly controlled so as to act as harmonic filter. It is seen that with the control action initiation, the PQ levels are improved. The results so obtained are in close agreement as compared with the benchmark data reported in the literature [23]. It is observed that the PQIs given in Table 5 are, slightly greater than the benchmark data. This is mainly due to the cyclic variations in the trend of load and wind data pattern considered, which focuses on the increaed concern towards use of power electronic converters.

Table 5. Verification of effectiveness of PQIs after installation of DFIG.

Different cases considered	**Indices**	**DG Location #17 DG capacity (MW)**			**Deviations in PQ levels?**	**Control actions initiated**	**DG Location #17 DG capacity (MW)**			**Deviations in PQ levels?**	**Bench mark Data [19]**
		1.65	***3.3***	***4.95***			**1.65**	**3.3**	**4.95**		
Case -a	SATHD_V_{DG}	1.75	1.42	1.14	No	Nil	-	-	-	No	--
	STHD95_V_{DG}	4.21	3.14	3.58							--
	SATHD_V_{DG}	2.1	2.03	1.89	Yes	Determines location of bus at which filter to be connected to the system using LSSVM	1.87	1.54	1.12	No	1.57
	STHD95_V_{DG}	5.12	4.97	4.85			4.89	4.76	4.73		4.04
Case -b	SATHD_V_{DG}	1.92	1.58	1.74	Yes	Determines location of bus at which filter to be connected to the system using LSSVM	1.62	1.21	1.05	No	1.57
	STHD95_V	5.32	4.91	4.83			4.94	4.72	4.68		4.04
	SATHD_V_{DG}	2.24	2.18	1.97	Yes		1.75	1.53	1.24	No	1.57
	STHD95_V_{DG}	5.23	5.14	5.08			4.95	4.87	4.61		4.04

4. Conclusion

Here, an algorithm has been proposed for establishing the impact of the DGs on distribution networks. From the analysis, it is observed that, there is improvement in the voltage and reduction of harmonics in case of SCIG. Similarly, improvement in the voltage is also observed in case of DFIG, but, power electronic interfaces of DFIG increases harmonic distortion. However, since the DFIG has more applications like variable speed control, etc., as compared to SCIG, they are widely used in practice. As such, to utilize the advantages of DFIG, some alternative arrangements should be made when DFIG type wind turbines are used to avoid the Power Quality deviations.

In this regard, the results presented in this work highlight about both positive and negative impacts of DGs. The positive impacts include, improvement in voltage at all buses for the both type DGs and decrease in harmonic distortions with SCIG. The negative impacts are the PQIs for DFIG, which are negative in most of the cases. To overcome this non-beneficial situation, an algorithm based on machine learning concepts is utilized to facilitate decision manager to initiate control actions. This is done by continuously tracking PQI and accordingly control signals/commands are generated. Although, in practice, to assess PQ levels, many researchers use PQ indices in terms of voltage regulation, phase unbalance, voltage sag/swell, transient over voltages, flickering, etc., here, the PQIs only related to harmonics are considered mainly due to the increased usage of power electronics in Electric Systems. The future scope of the work includes, validation of the present work for a fairly large, real size, distribution network and there by development of a hardware prototype to implement PQ improvement by incorporating suitable control actions, so as to ensure overall improvement of Power Quality.

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