The Analysis of Voltage Increase Phenomena in a Distribution Network with High Penetration of Distributed Generation

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***Abstract*—Various distributed generation (DG) systems with capacities in the range of several kilowatts to tens of megawatts can increase voltage along a feeder when they are injecting power into distribution systems. Thus, the main objective of this study is to analyze the transient behavior of such a distribution system integrated by DG systems. This study (1) models the IEEE 37-bus test feeder as a distribution network enhanced by DG systems in Simulink of MATLAB; (2) proposes case studies of DG systems with their total capacity of 10 and 38 percent of the feeder rating; and then (3) simulates the transient behavior of the test feeder when DG systems inject active power at the unity power factor during a few cycles of 60 Hz. Finally, it addresses the issues of an increase in voltage resulting from the installation of DG systems in a transient state.**

***Index Terms*--Distributed generation (DG), transient behavior of a distribution network, and an increase in voltage**

I. Introduction

The deployment of distributed generation (DG) systems in distribution networks reduces energy consumption because of the active power injected by the systems (reverse power flow). However, they can also cause transient overvoltage when they inject power into distribution networks.

During the last two decades, many studies have analyzed the transient behavior of distribution networks enhanced by various DG systems. One study modeled lighting, resistive, and induction motor loads by their active and reactive power equations, generated disturbances by voltage dips caused by a short circuit, and examined the short-circuit transient study of radial distribution networks enhanced by such loads [1]. Another study, using Simulink of MATLAB, performed transient simulations of the IEEE 13-node test feeder enhanced by a gas turbine and a diesel engine generator, installed a thyristor-controlled braking resistor (TCBR) to damp the oscillation of the test feeder that experiences disturbances, and analyzed the effectiveness of a TCBR [2]. Also using Simulink of MATLAB, another study generated a fault on an actual distribution network enhanced by five synchronous-type DG systems with a capacity of 30 MVA, disconnected and resynchronized the five DG systems either with or without accordance to IEEE Standard 1547, and examined their transient impact on a distribution network [3]. A recent study using Simulink of MATLAB modeled a 10-kV distribution network that incorporated three squirrel cage induction generators, a diesel generator, and twenty microturbines, analyzed the transient behavior of DG systems during the post-fault period and the impact of DG systems on protection, and proposed that each type of DG have a unique setting for undervoltage protection [4]. In 2010, one study modeled superconducting fault current limiters (SFCLs) installed in a 154/22.9 kV substation with the Electromagnetic Transient Program (EMTP), generated a fault in 0.1 seconds of the simulation, and examined the recovery characteristics of SFCLs and the schemes of reclosers [5]. Another study, using MATLAB and EMTP-Restructured Version (EMTP-RV), analyzed the transient behavior of large-scale distribution networks reconfigured by switching on and off breakers and examined the self-healing principles of a real metropolitan distribution network [6]. More recently, another study modeled a distribution network with 230/24 kV transformers in the EMTP Real-Time Digital Simulator (RTDS) and RSCAD, added photovoltaic (PV) plants with high penetration capacity, and simulated the transient behavior of such a distribution network [7]. Most of these studies have performed short-circuit analyses, but they did not examine (1) voltage variation (which is not triggered by a short circuit) when DG systems inject active power into the distribution network and (2) load factors of a substation, which can be defined by the ratio of the capacity of the local loads to the total peak load [8]. In addition, they did not model rapid variations in renewable DG generation, particularly the PV system in this study, that result from fast moving clouds and weather disturbances in the atmosphere. To analyze the effect of a sudden increase in voltage caused by such variations in DG generation with relatively high capacity on a distribution network, this study (1) proposes the IEEE 37-bus test feeder as a distribution network; (2) models the test feeder enhanced by DG systems in Simulink of MATLAB; and (3) simulates the transient behavior of the test feeder when DG systems inject power at a power factor of unity or 1.0 during a few cycles.

This paper is organized as follows: Section 2 describes the problem statement; Section 3 presents the modeling of a distribution network consisting of lines, transformers, distributed generators, and other components; Section 4 introduces a case study to solve the proposed problem. Section

5 discusses the transient behavior of the case study; and then Section 6 summarizes major conclusions.

II. PROBLEM STATEMENT

To analyze the effect of the DG system on an increase in voltage resulting from DG systems installed on distribution networks during the transient state, this study proposes the following three scenarios:

(1) *Equal-capacity DG systems*. Ten DG systems (arbitrarily selected because the optimal allocation of the capacities and the locations of DG systems is outside the scope of this study) are dispersed across the distribution network, as shown in Figure 1. This study assumes that the main transformer with a capacity of 25 MVA and line-to-line voltages of 138 kV and 13.09 kV supplies power to the test feeder (shown in Figure 1). To determine the impact of DG systems on the transient behavior of the distribution network, this study assumes that ten DG systems with their total capacity of ten percent of the assumed feeder rating (25 MVA) inject active power into the test feeder. In other words, each DG system provides 0.25 MVA, a total of 2.5 MVA from the ten DG systems, one second after starting the simulation. That is, all switches connected to the ten DG systems turn on in t=1 second.

(2) *A single heavy-capacity DG system and the other small-capacity DG systems*. In this scenario, a single heavy-capacity DG system has a capacity of 2.25 MVA (90 percent of 2.5 MVA) and the other nine DG systems have a total capacity of 0.25 MVA. Since a single heavy-capacity DG system can be any one of the ten DG systems in Figure 1, this study simulates two cases. In the first case, a heavy-capacity DG system is on bus 702 (which is closest to the main transformer among the ten DG buses). In the second case, a heavy-capacity DG system is on bus 740 (which is the farthest from the main transformer).

(3) *High penetration of DG systems*. One study nearly optimally allocated the locations and the capacities of DG systems installed on the IEEE 37-bus test feeder at peak load while minimizing voltage variations from 1.0 per unit (PU) of the distribution network in the steady state. The study optimally allocated four DG systems with their total capacity of 38 percent of the feeder rating when they inject only active power at the unity power factor. This study uses the optimal locations and capacities proposed by the study [9] as a scenario of high-penetration DG systems.

III. MODELING OF THE DISTRIBUTION SYSTEM

The IEEE PES Distribution System Analysis Subcommittee proposed 4-, 13-, 34-, 37-, 123-, and 8,500-bus feeders for the purposes of research [10, 11]. This study modified the IEEE 37-bus test feeder as a distribution network using Simulink. The local loads of the test feeder consist of thirteen delta-connected constant power loads, six delta-connected constant current loads, and six delta-connected constant impedance loads at their fixed locations, supplied by a three-phase transformer of 25 MVA. The load factor is the ratio of the total capacity of local loads to the total peak load of the distribution network as follows [8]:

$$Load\ Factor = \Big(\sum_{i \in \{All\ Feeders\}} P_{i,Load}\Big) / \ Total\ Peak\ Load\ , \qquad (1)$$

where $P_{i,Load}$ = the power of local individual loads on distribution feeder *i* in kVA or MVA.

This study examines various load factors such as 50, 80, and 100 percent (which correspond to a total load of 12.5, 20, and 25 MVA, respectively) of the test feeder.

A. Modeling of the Distribution Line

All lines of the test feeder in Figure 1 are undergrounded at spacing distances shown in Figure 2. Cable data such as conductor sizes, the insulation diameter, the screen diameter, and the outside diameter are from [10]. From these spacing distances and cable data, Pi-equivalent parameters are calculated by the "RLC Cable Parameters Tool" of MATLAB. Tables 6 and 7 illustrate resistance matrices in *Ω/km*, inductance matrices in *H/km*, and capacitance matrices in *μF/km* for each underground cable in the Appendix. Since each cable consists of an inner phase conductor and an outer screen conductor, the dimension of each matrix for a three-phase system is 6 × 6. This study uses these impedance data as input data to the proposed simulation model in Simulink of MATLAB.

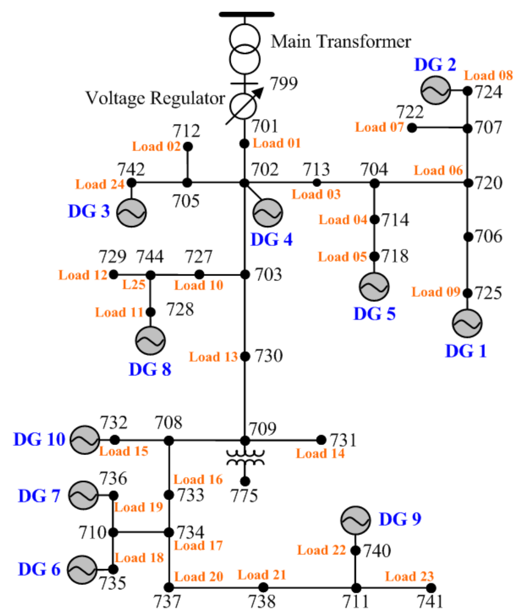


Figure 1. The IEEE 37-bus test feeder.

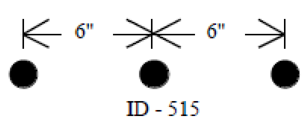


Figure 2. Spacing of underground cables [10].

B. Modeling of the Transformer

This study uses a transformer with line-to-line voltages of 138 kV and 13.09 kV in the test feeder, which is modeled in

Simulink of MATLAB [12]. TABLE I shows the transformer with a winding resistance of 0.008 PU and a leakage reactance of 0.08 PU at an X/R ratio of 10.

C. *Modeling of the DG System*

Using Simulink of MATLAB, this study models the DG system as a generator with an X/R ratio of 22.5 [13] and a sub-transient reactance of 0.13 PU [14], shown in TABLE II.

TABLE I. TRANSFORMER DATA

Category		Actual Value	PU
Nominal Power		25 MVA	1.0
Line-to-line Voltage [12]		138 kV/13.09 kV	1.0/1.0
Frequency		60 Hz	1.0
Primary	Winding Resistance (R)	3.047 Ω	0.004 (0.4 %)
	Leakage Reactance (X) [10]	30.47 Ω	0.04 (4 %)
Secondary	Winding Resistance (R)	0.0274 Ω	0.004 (0.4 %)
	Leakage Reactance (X) [10]	0.274 Ω	0.04 (4 %)

TABLE II. A DG SYSTEM IN A SCENARIO OF EQUAL-CAPACITY DG SYSTEMS

Category	Actual Value	Per Unit
Line-to-Line Voltage	13.09 kV	1.0 PU
Frequency	60 Hz	1.0 PU
Short-Circuit Power	0.25 MVA	1.0 PU
Source Sub-transient Reactance (X''_d) [14]	89.10 Ω (0.236 H)	0.13 PU
X/R Ratio [13]	22.5	22.5
Source Resistance (R)	3.955 Ω	0.00577 PU
PQ Load (Power Factor)	0.25 MW (1.0 Power Factor)	1.0 PU

D. *Modeling of the Other Components*

Since a slack bus with a voltage magnitude of unity PU (or 1.0 PU) is usually used for steady-state analysis, this study connects an ideal voltage source to the primary side (the high-voltage side) of the main transformer in Figure 1. Since voltage regulation for power transformers with an on-load tap changer (OLTC) (connected to the secondary, or low-voltage, side of the main transformer in Figure 1) operates on a time scale of tens of seconds to a few minutes from the point of view of relatively long-term voltage stability [15]. However, since this study analyzes the transient behavior of the distribution network during only a few cycles of 60 Hz when DG systems are injecting their power into the distribution network, voltage regulators are not considered. Nevertheless, a combination of voltage regulators and high-capacity DG systems (with the capability of reactive power control) can provide better voltage regulation for dynamic load conditions.

IV. CASE STUDY

The objective of this case study is to analyze the transient behavior of the distribution network enhanced by ten DG systems with a total capacity of 2.5 MVA (ten percent of the assumed feeder rating) during a few cycles. For this purpose, this study modifies the IEEE 37-bus test feeder as an example of a distribution network in Simulink of MATLAB and assumes three scenarios. One is a scenario of equal-capacity DG systems, another a heavy-capacity DG system and the other small-capacity DG systems, and the other relatively high-capacity DG systems.

V. TRANSIENT BEHAVIOR OF THE DISTRIBUTION NETWORK

A. *Equal-Capacity DG Systems*

This study assumes that ten equal-capacity DG systems with a total capacity of 2.5 MVA (ten percent of a feeder rating of 25 MVA) inject active power one second after starting a simulation. Therefore, in the scenario of the equal-capacity DG systems, ten DG systems (each with a capacity of 0.25 MVA) will inject only active power after one second. That is, all switches connected to the ten DG systems turn on at one second. Figure 3 shows the total root-mean-square (RMS) active and reactive power of the test feeder in PU when ten DG systems inject power at a load factor of 100 percent. This study uses a base of 25 MVA. Since ten DG systems inject 2.5 MW (at the unity power factor) at one second, the total active and reactive power (at the slack bus) of the test feeder decreases from 0.90 to 0.85 PU and 0.43 to 0.37 PU, respectively. Figure 4 presents the RMS line-to-neutral voltages of the secondary side of the transformer in PU. An active power injection of 2.5 MW increases the voltage (from 0.952 to 0.959 PU) in the secondary side of the transformer at one second after the start of the simulation.

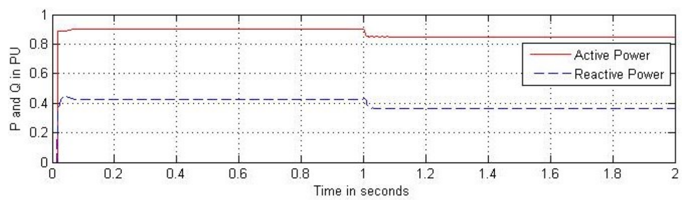


Figure 3. Total RMS active and reactive power of the test feeder at a load factor of 100 percent in PU.

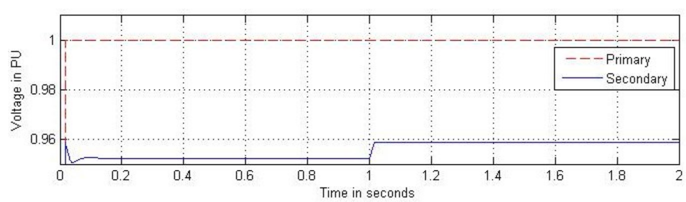


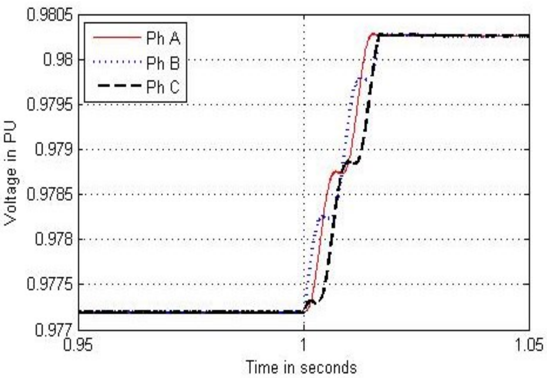
Figure 4. RMS line-to-neutral voltages of the secondary side of the transformer at a load factor of 100 percent in PU.

Figure 5 shows the line-to-neutral RMS voltages of the secondary side of the transformer during a few cycles. At load factors of 50, 80, and 100 percent, the change ratios of the voltages after one second, or between 0.95 and 1.05 seconds, are +0.31, +0.52, and +0.67 percent, respectively. The differences in the voltages after one second are +0.00307 PU (=0.98026-0.97719 PU), +0.00503 PU (=0.96759-0.96256 PU), and +0.00641 PU (=0.95873-0.95232 PU), respectively. Therefore, this study can conclude the following:

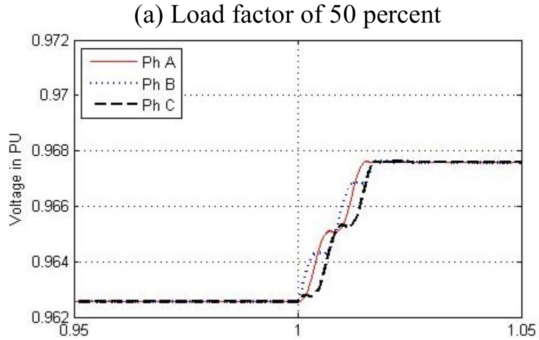
(1) As the load on the distribution network increases, the voltages of the network (caused by power injected by DG systems) increase (e.g., +0.00307 PU=0.98026-0.97719 PU in the case of a load factor of 50 percent and

+0.00641 PU=0.95873-0.95232 PU in the case of a load factor of 100 percent).

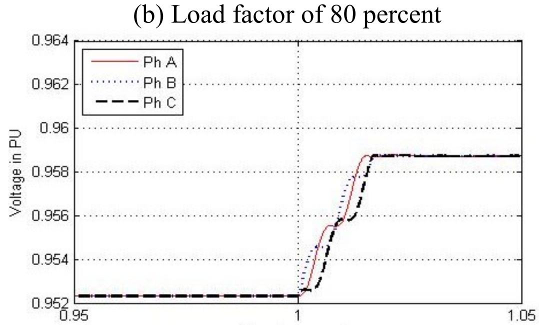
(2) The impact of ten equal-capacity DG systems with a total capacity of ten percent of the feeder rating on an increase in voltage of a distribution system is not significant.



(a) Load factor of 50 percent



(b) Load factor of 80 percent



(c) Load factor of 100 percent

Figure 5. RMS line-to-neutral voltages of the secondary side of the transformer in PU.

B. A Heavy-Capacity DG System and the Other Small-Capacity DG Systems

In this scenario, a single DG system has a capacity of 2.25 MVA (90 percent of 2.5 MVA) and the other nine DG systems have a total capacity of 0.25 MVA (10 percent of 2.5 MVA). Since a single heavy-capacity DG system can be one of the ten DG systems in Figure 1, this study simulates two cases. The former is a case in which a heavy DG system is on bus 702 (the closest to the main transformer among the ten DG buses in Figure 1). The latter, a heavy DG system, is on bus 740 (the farthest from the main transformer in Figure 1). TABLE III illustrates the line-to-neutral voltages of all the buses of the test feeder with a load factor of 100 percent, the worst case according to the conclusion in the previous section. From TABLE III, this study concludes that the DG system installed on bus 740 increases voltage more than the DG system on bus 702; that is, a heavy DG system installed on a bus farthest from a main transformer causes a larger increase in voltage. Since this study does not apply to a voltage regulator (described in Section III.D), some voltages of the test feeder at a load factor of 100 percent are below 0.90 PU. Note that this study analyzes an increase in the voltage of a distribution network when DG systems are injecting power into the distribution network.

C. High Penetration of DG Systems

In this scenario, four optimal DG systems that minimize voltage variations from 1.0 PU in a steady state have a total capacity of 38 percent of 25 MVA (DG systems on bus 701, 732, 710, and 740 have 6, 11, 13, and 8 percent, respectively) [9]. TABLE IV shows the line-to-neutral voltages and the currents of ten representative buses of the test feeder enhanced by optimal DG systems with a capacity of 38 percent of the feeder rating at a load factor of 100 percent. Since the voltage differences between 0.95 and 1.05 seconds lie within a range of 0.02 PU (on the secondary side of the transformer) to 0.06 PU (on bus 740), the impact of the DG systems on an increase in voltage is significant, even when the voltage increases by 0.06 PU (6%). Since this study does not apply to a voltage regulator, some voltages of the test feeder at a load factor of 100 percent fall below 0.90 PU.

If (1) all the DG systems in operation on the test feeder were disconnected from the grid (but at a very low probability) or (2) all the PV systems clustered on the test feeder experienced fast-moving clouds, they might affect the operation of overcurrent protection devices (e.g., fuses, reclosers, and relays). For example, if all the four DG systems at their full capacities were suddenly disconnected, the magnitude of current on the secondary side of the transformer could increase from 854.1 A to 1153.9 A, shown in TABLE IV. In fact, DG systems with a relatively high capacity of 38 percent may disrupt the overall coordination of overcurrent because of the possibility of sudden increases in the magnitude of the current.

TABLE III. VOLTAGE VARIATIONS OF ALL BUSES AT A LOAD FACTOR OF 100 PERCENT

Bus	Heavy DG Bus: 702 (close to the main transformer)				Heavy DG Bus: 740 (far from the main transformer)			
	Voltage (0.95 Sec)=A	Voltage (1.05 Sec)=B	Percent Change from A to B	Difference (B-A)	Voltage (0.95 Sec)=A	Voltage (1.05 Sec)=B	Percent Change from A to B	Difference (B-A)
	PU	PU	%	PU	PU	PU	%	PU
Slack	1.000	1.000	0	0	1.000	1.000	0	0
Transformer Secondary	0.952	0.958	+0.58	+0.0055	0.952	0.960	+0.76	+0.0073
701	0.931	0.938	+0.76	+0.0071	0.931	0.940	+0.98	+0.0091
712	0.914	0.922	+0.93	+0.0085	0.914	0.925	+1.18	+0.0107
713	0.912	0.922	+1.06	+0.0097	0.912	0.923	+1.18	+0.0108
714	0.906	0.916	+1.08	+0.0098	0.906	0.917	+1.20	+0.0109
718	0.905	0.915	+1.08	+0.0098	0.905	0.916	+1.20	+0.0109
720	0.900	0.910	+1.10	+0.0099	0.900	0.911	+1.22	+0.0109
722	0.895	0.904	+1.11	+0.0099	0.895	0.905	+1.23	+0.0110
724	0.894	0.904	+1.11	+0.0099	0.894	0.905	+1.23	+0.0110
725	0.899	0.909	+1.10	+0.0099	0.899	0.910	+1.22	+0.0110
727	0.902	0.911	+0.95	+0.0086	0.902	0.915	+1.42	+0.0128
728	0.900	0.909	+0.96	+0.0087	0.900	0.913	+1.43	+0.0129

729	0.901	0.909	+0.96	+0.0086	0.901	0.913	+1.43	+0.0129
730	0.892	0.900	+0.98	+0.0087	0.892	0.907	+1.71	+0.0153
731	0.887	0.896	+0.99	+0.0088	0.887	0.903	+1.81	+0.0161
732	0.882	0.891	+1.01	+0.0089	0.882	0.899	+1.98	+0.0175
733	0.877	0.886	+1.02	+0.0089	0.877	0.896	+2.14	+0.0188
734	0.869	0.878	+1.04	+0.0091	0.869	0.890	+2.42	+0.0211
735	0.867	0.876	+1.05	+0.0091	0.867	0.888	+2.44	+0.0212
736	0.866	0.875	+1.06	+0.0091	0.866	0.887	+2.45	+0.0212
737	0.863	0.872	+1.06	+0.0091	0.863	0.886	+2.73	+0.0236
738	0.860	0.869	+1.06	+0.0091	0.860	0.885	+2.93	+0.0252
740	0.858	0.867	+1.07	+0.0092	0.858	0.886	+3.22	+0.0276
741	0.858	0.868	+1.07	+0.0092	0.858	0.885	+3.11	+0.0267
742	0.914	0.922	+0.93	+0.0085	0.914	0.925	+1.18	+0.0108
744	0.901	0.910	+0.96	+0.0086	0.901	0.914	+1.43	+0.0128
Average	0.896	0.905	+0.97	+0.0086	0.896	0.911	+1.68	+0.0148

TABLE IV. VOLTAGE AND CURRENT VARIATIONS PRODUCED BY FOUR DG SYSTEMS WITH A CAPACITY OF 38 PERCENT OF 25 MVA (AT A LOAD FACTOR OF 100 PERCENT)

Bus	Voltage				Current			
	Voltage (0.95 Sec)=A	Voltage (1.05 Sec)=B	Percent Change from A to B	Difference (B-A)	Current (0.95 Sec)=A	Current (1.05 Sec)=B	Percent Change from A to B	Difference (B-A)
	PU	PU	%	PU	A	A	%	PU
Slack	1.000	1.000	0	0	110.2	81.7	-25.84	-28.5
Transformer Secondary	0.952	0.971	+1.91	+0.0182	1153.9	854.1	-25.98	-299.8
712	0.914	0.942	+3.06	+0.0280	41.5	40.3	-3.0	-1.2
714	0.906	0.934	+3.09	+0.0280	51.3	52.3	2.07	1.1
720	0.900	0.928	+3.12	+0.0280	152.5	151.1	-0.91	-1.4
727	0.902	0.936	+3.74	+0.0337	124.0	120.2	-3.07	-3.8
730	0.892	0.933	+4.59	+0.0409	400.6	169.3	-57.73	-231.2
736	0.866	0.923	+6.60	+0.0572	16.4	17.5	6.61	1.1
738	0.860	0.918	+6.72	+0.0578	128.9	64.2	-50.21	-64.7
740	0.858	0.918	+6.95	+0.0597	44.2	41.3	-6.51	-2.9

TABLE V shows the minimum and maximum change ratios of increases in voltage in the case of the proposed three scenarios. The ratios of the voltage increases produced by DG systems with a capacity of 10 percent of the feeder rating lie within a range of +0.31 to +3.22 percent. Thus, the impact of DG systems with a total capacity of ten percent of the feeder rating on an increase in voltage can be small. However, the ratios of voltage increases produced by DG systems with a capacity of 38 percent fall within a range of +0.88 to +6.95 percent, indicating that the impact of DG systems with a capacity of 38 percent on an increase in voltage can be significant.

TABLE V. CHANGE RATIOS OF INCREASES IN VOLTAGE IN ALL SCENARIOS

Total DG Capacity in %	DG Bus	Load Factor		
		50%	80%	100%
10 %	725,724,742,702,718, 735,736,728,740,732	0.31 % ~ 0.74 %	0.52 % ~ 1.27 %	0.67 % ~ 1.68 %
10 %	725,724,742,702(Heavy DG),718, 735,736,728,740,732	0.35 % ~ 0.50 %	0.58 % ~ 0.85 %	0.76 % ~ 1.11 %
10 %	725,724,742,702,718, 735,736,728,740(Heavy DG),732	0.45 % ~ 1.41 %	0.76 % ~ 2.43 %	0.98 % ~ 3.22 %
38 %	701, 710, 732, 740	0.88 % ~ 3.05 %	1.48 % ~ 5.26 %	1.91 % ~ 6.95 %

VI. CONCLUSION

This study analyzed the transient behavior of a distribution network when DG (distributed generation) systems inject power into the distribution network. For this purpose, this study has (1) modeled the IEEE 37-bus test feeder as an example of a distribution network using Simulink of MATLAB; (2) performed three scenarios (one a scenario of equal-capacity DG systems with their total capacity of ten percent of the feeder rating, another a scenario of a heavy-capacity DG system and the other small-capacity DG systems with their total capacity of 10 percent, and the last a scenario of optimal DG systems with a capacity of 38 percent of the feeder rating); and (3) analyzed the impact of DG systems from the point of view of not only an increase in voltage caused by active power injected by the DG system but also the overall coordination of overcurrent that may be disrupted by reverse power flow.

The results from the transient analysis of a modified version of the IEEE 37-bus test feeder in the two scenarios of DG systems with their total capacity of 10 percent showed the change ratios of the line-to-neutral voltages in a range of +0.31 to +3.22 percent. Therefore, this study concludes that the impact of DG systems with a total capacity of ten percent of the feeder rating on an increase in voltage is not significant. In the first scenario of ten equal-capacity DG systems with their total capacity of ten percent of the feeder rating, the differences in the voltages after one second were +0.00307 PU (a load factor of 50 percent), +0.00503 PU (a load factor of 80 percent), and +0.00641 PU (a load factor of 100 percent). Therefore, we conclude that as the load on the distribution network increases, the voltages of the network caused by power injected by DG systems increase. In the second scenario of a heavy-capacity DG system and the other small-capacity DG systems, this study confirmed that a heavy DG system farthest from a main transformer has a greater impact on voltage levels than a heavy DG system closest to a main transformer. Lastly, in the scenario of four optimal DG systems with their total capacity of 38 percent of the feeder rating, since voltage differences between 0.95 and 1.05 seconds lie within a range of 0.02 to 0.06 PU, the impact of the DG systems on an increase in voltage is significant.

This study treated a DG system as a generator in operation on a P-Q bus that provides only active power at unity power factor. However, various power factors of loads and DG systems can worsen the voltage rise. Furthermore, the transient behavior of the distribution network triggered by various renewable DG systems such as PV systems and wind farms (which contain considerably more disturbance in their output) at various power factors can differ from that found by this study. This study also did not apply to a voltage regulator and DG systems with the capability of Volt/Var control (i.e., DG systems can inject or absorb reactive power to maintain a bus voltage within a specified range, typically within 0.95 to 1.05 PU of the rated voltage level), but it could be extended to such cases by implementing a voltage regulator such as an OLTC transformer and by introducing actual renewable systems such as PV systems, wind farms, and microturbines with the capability of Volt/Var control under various load conditions.

VII. APPENDIX

TABLE VI. PI-EQUIVALENT PARAMETERS FOR R AND L

ID	6×6 R in *Ohm/km*						6×6 L in *H/km*					
721	0.2284	0.0592	0.0592	0.0592	0.0592	0.0592	0.0023	0.0021	0.0017	0.0017	0.0017	0.0017
	0.0592	0.1385	0.0592	0.0592	0.0592	0.0592	0.0021	0.0021	0.0017	0.0017	0.0017	0.0017
	0.0592	0.0592	0.2284	0.0592	0.0592	0.0592	0.0017	0.0017	0.0023	0.0021	0.0017	0.0017
	0.0592	0.0592	0.0592	0.1385	0.0592	0.0592	0.0017	0.0017	0.0021	0.0021	0.0017	0.0017
	0.0592	0.0592	0.0592	0.0592	0.2284	0.0592	0.0017	0.0017	0.0017	0.0017	0.0023	0.0021
	0.0592	0.0592	0.0592	0.0592	0.0592	0.1385	0.0017	0.0017	0.0017	0.0017	0.0021	0.0021
722	0.3953	0.0592	0.0592	0.0592	0.0592	0.0592	0.0023	0.0022	0.0017	0.0017	0.0017	0.0017
	0.0592	0.1903	0.0592	0.0592	0.0592	0.0592	0.0022	0.0022	0.0017	0.0017	0.0017	0.0017
	0.0592	0.0592	0.3953	0.0592	0.0592	0.0592	0.0017	0.0017	0.0023	0.0022	0.0017	0.0017
	0.0592	0.0592	0.0592	0.1903	0.0592	0.0592	0.0017	0.0017	0.0022	0.0022	0.0017	0.0017
	0.0592	0.0592	0.0592	0.0592	0.3953	0.0592	0.0017	0.0017	0.0017	0.0017	0.0023	0.0022
	0.0592	0.0592	0.0592	0.0592	0.0592	0.1903	0.0017	0.0017	0.0017	0.0017	0.0022	0.0022
723	1.2808	0.0592	0.0592	0.0592	0.0592	0.0592	0.0025	0.0022	0.0017	0.0017	0.0017	0.0017
	0.0592	0.3277	0.0592	0.0592	0.0592	0.0592	0.0022	0.0022	0.0017	0.0017	0.0017	0.0017
	0.0592	0.0592	1.2808	0.0592	0.0592	0.0592	0.0017	0.0017	0.0025	0.0022	0.0017	0.0017
	0.0592	0.0592	0.0592	0.3277	0.0592	0.0592	0.0017	0.0017	0.0022	0.0022	0.0017	0.0017
	0.0592	0.0592	0.0592	0.0592	1.2808	0.0592	0.0017	0.0017	0.0017	0.0017	0.0025	0.0022
	0.0592	0.0592	0.0592	0.0592	0.0592	0.3277	0.0017	0.0017	0.0017	0.0017	0.0022	0.0022
724	1.4844	0.0592	0.0592	0.0592	0.0592	0.0592	0.0025	0.0023	0.0017	0.0017	0.0017	0.0017
	0.0592	0.3671	0.0592	0.0592	0.0592	0.0592	0.0023	0.0023	0.0017	0.0017	0.0017	0.0017
	0.0592	0.0592	1.4844	0.0592	0.0592	0.0592	0.0017	0.0017	0.0025	0.0023	0.0017	0.0017
	0.0592	0.0592	0.0592	0.3671	0.0592	0.0592	0.0017	0.0017	0.0023	0.0023	0.0017	0.0017
	0.0592	0.0592	0.0592	0.0592	1.4844	0.0592	0.0017	0.0017	0.0017	0.0017	0.0025	0.0023
	0.0592	0.0592	0.0592	0.0592	0.0592	0.3671	0.0017	0.0017	0.0017	0.0017	0.0023	0.0023

TABLE VII. PI-EQUIVALENT PARAMETERS FOR C IN μF/KM

ID	6×6 C in *μF/km*						ID	6×6 C in *μF/km*					
721	0.2586	-0.2586	-0.0001	-0.0001	-0.0001	-0.0001	723	0.1416	-0.1416	-0.0001	-0.0001	-0.0001	-0.0001
	-0.2586	1.1158	-0.0001	-0.0001	-0.0001	-0.0001		-0.1416	0.9947	-0.0001	-0.0001	-0.0001	-0.0001
	-0.0001	-0.0001	0.2586	-0.2586	-0.0001	-0.0001		-0.0001	-0.0001	0.1416	-0.1416	-0.0001	-0.0001
	-0.0001	-0.0001	-0.2586	1.1158	-0.0001	-0.0001		-0.0001	-0.0001	-0.1416	0.9947	-0.0001	-0.0001
	-0.0001	-0.0001	-0.0001	-0.0001	0.2586	-0.2586		-0.0001	-0.0001	-0.0001	-0.0001	0.1416	-0.1416
	-0.0001	-0.0001	-0.0001	-0.0001	-0.2586	1.1158		-0.0001	-0.0001	-0.0001	-0.0001	-0.1416	0.9947
722	0.2125	-0.2125	-0.0001	-0.0001	-0.0001	-0.0001	724	0.1154	-0.1154	-0.0001	-0.0001	-0.0001	-0.0001
	-0.2125	1.0842	-0.0001	-0.0001	-0.0001	-0.0001		-0.1154	0.8790	-0.0001	-0.0001	-0.0001	-0.0001
	-0.0001	-0.0001	0.2125	-0.2125	-0.0001	-0.0001		-0.0001	-0.0001	0.1154	-0.1154	-0.0001	-0.0001
	-0.0001	-0.0001	-0.2125	1.0842	-0.0001	-0.0001		-0.0001	-0.0001	-0.1154	0.8790	-0.0001	-0.0001
	-0.0001	-0.0001	-0.0001	-0.0001	0.2125	-0.2125		-0.0001	-0.0001	-0.0001	-0.0001	0.1154	-0.1154
	-0.0001	-0.0001	-0.0001	-0.0001	-0.2125	1.0842		-0.0001	-0.0001	-0.0001	-0.0001	-0.1154	0.8790

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