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Estimation of Voltage Profile and Short-Circuit Currents for a Real Substation Distribution System

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ABSTRACT Electrical energy demands gradually increasing in the world in each year, and numerous power plants continue to be installed to supply required energy. Most of these are small-scale power plants established at different terrains. The power produced by the power plants is transmitted to the existing transmission and distribution lines in the Black Sea region of Turkey. So, the electrical network is becoming increasingly complex. Distributed generations affect the electrical system in many ways. The goal of this study is to determine the effects of distributed generation on Trabzon city's Araklı-II feeder such as voltage profile and short-circuit currents of bus bars. The system modeled and simulated by using the DIgSILENT Power Factory software with real parameters. It was found that distributed generation sources have positively affected the voltage level of bus bars yet highly single-phase and three-phase short-circuit currents was observed.

Keywords: Load Flow, Short Circuit Analysis, Distributed Generation, Radial Distribution System

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1. INTRODUCTION

Both demand and supply of electricity is continuously increasing in the world due to population growth and industrial development [1]. As a result, several distributed generators (DGs) have been are built to be used in electric power plants recent years in Turkey [2]. These power plants are usually located close to the energy source and the existing distribution network [3]. DGs are connected to radial network and change the voltage profile and short circuit current [4]. The electrical devices work efficiently if the voltage profile and stability is in the range of nominal values. In addition, relay protection and coordination are very important for power stability [5].Coordination of electrical systems mostly depends on the voltage level and short-circuit currents value. Nowadays, these parameters are calculated using by software instead of conventional methods [6]. Arsin substation center contains industrial feeder, household feeders and two DGs which are connected to the different points of busbar. This connecting situation of DGs on busbar is the reason for choosing this substation as study of interest. This study aims to report the changes in voltage profile, single phase-ground and three phase short- circuit currents on busbar and terminals according to electric generation parameters of DGs.

2. ANALYSES OF FEEDERS

Single line diagram of the Arsin substation is shown in Figure 1. Arsin substation has two power transformers (TR). TR-A's is 25 MVA power transformers while TR-B's power is 50 MVA. When higher electrical power is demanded from substation, both of two transformers are activated, otherwise only TR-B is activated. The vector group of these transformers designed as YNyn0. The neutral point of the primer side of power transformers grounded directly and neutral point of secondary side is grounded over 20 ohm resistance, separately. Line diagram of Araklı-II feeder is shown in Figure 2. DG-I and DG-II are 14 km and 19 km away from the transformer center, respectively.

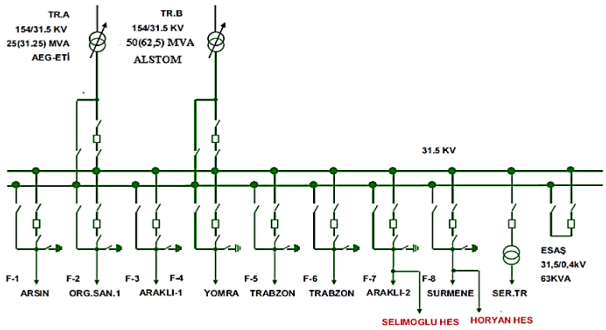

Fig. 1. Single-line diagram of Arsin substation [7]

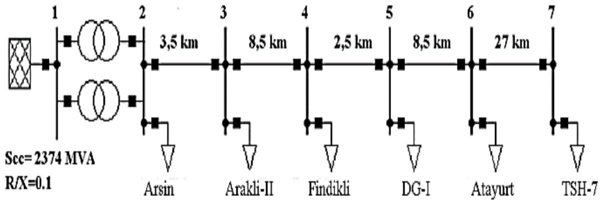

Fig. 2. Single-line diagram of Araklı-II feeder

The substation center and all feeders which were modeled using DIgSILENT Power Factory software are seen in Figure 3. This established model was based on data provided from Çoruh Electricity Distribution Company (Çoruh EDAS Corp.) and which is one of the 14 district offices of Turkey Electricity Transmission Company (TEIAS). The network model was examined with four cases according to the situation of DGs. These cases are, both DGs deactivated (Case-I), only DG-I activated (Case-II), only DG-II activated (Case-III), and both DGs activated (Case-IV). The delivery power which is used for load flow analysis are selected as the lowest and highest powers recorded on distribution grid system in January 2015. Also, load flow estimation analyses were performed for the years of 2020 and 2025. In addition, short-circuit current for single-phase to ground and three-phase were calculated in selected bus bar.

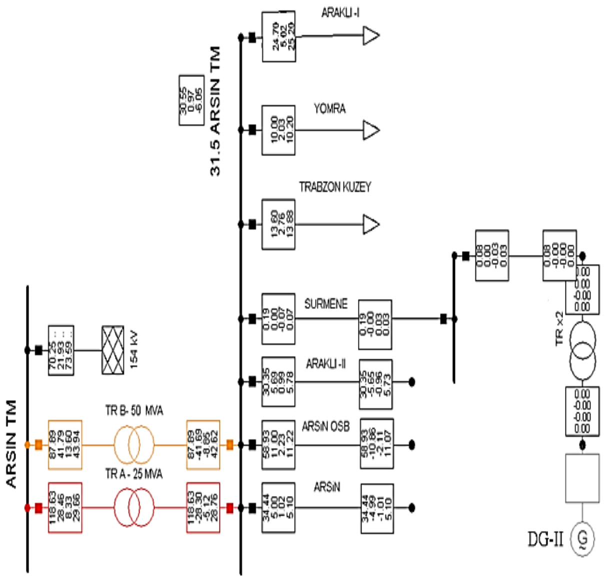

Fig. 3. Çoruh EDAS Corp. Arsin substation loading estimation model for year 2025 without DGs

Short relative circuit voltage value (U_k %) of TR-A and TR-B are reported as 9.1 % and 12.3 % respectively. Maximum three-phase short-circuit current value of Arsin substation center is 8.9 kA and short-circuit cutting power value is 2374 MVA [7]. Two different DGs are connected to substation from two different points of feeders. Each power plant has two generator units which are running in parallel mode. The characteristics of these generators are given in Table 1. Generator stator windings are grouped in star type. Output voltage values of stator windings for DG-I and DG-II are 6.3 kV. On the other hand, neutral resistance values of stator windings are 365 ohm and 364 ohm respectively. Vector groups of voltage step-up transformers is Dyn11 (delta-grounded wyes) type and their nominal powers are 5.5 MVA, 3.375 MVA, respectively. The relative short circuit voltage U_k % value of these transformers is 7% and neutral resistance values are 20 ohm.

Table 1. Technical information of DG

DG-I	Xd	1.409	Xq	1.394
	X'd	0.259	X'q	1.394
	X"d	0.186	X"q	0.237
	P(MW)	4.5	Cosφ	0.90
DG-II	Xd	1.123	Xq	0.620
	X'd	0.211	X'q	0.620
	X"d	0.157	X"q	0.185
	P(MW)	3	Cosφ	0.85

The length of the Araklı -II line is 50 km long and radial type. DG-I is connected to this line. On the other hand, DG-II is connected to the substation with a separate 477 MCM line. Araklı-II feeder has 99 distribution transformers. Total nominal power for each of these transformers is about 10 MVA as shown in Table 2. These transformers have a different connection groups according to their rated power. Yzn11 connection group which have a nominal power value of 160kVA and below is used in transformers while Dyn11 connection group is used in transformers which have a nominal power value above 160 kVA.

Table 2. Technical information and quantity of transformer on Arakli-II feeder

Power (kVA)	50	100	160	250	400
Quantity	37	49	7	3	3
U_k %	4.5	4.5	4.5	4.5	4.5

2.1. Voltage Profile

DG can change the feeder voltages, and voltage drop is caused by the line impedance and current. The allowable voltage limits are defined in regulation [8]. According to IEC 1547 standards DGs are not expected to support the voltage control, actively. Nevertheless, voltage of the feeder can be changed by the DG type and operation region (grid sub excited or overexcited) [9]. Many values such as network power losses, amplitude of the busbar voltage, angle and power values are calculated using basic variables such as; Q: Reactive Power, P: Active Power, V: Busbar Voltage and δ: Phase Angle.

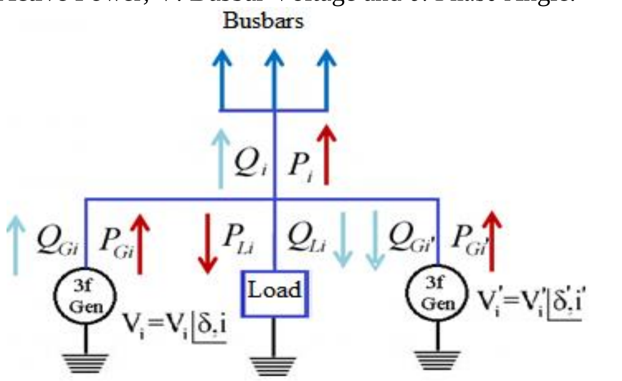

Fig. 4. Representation of basic load flow

Basic load flow scheme is shown in Figure 4. The generator transmits active power to the grid. However, the reactive power exchange is bidirectional. Particularly distributed generation sources use the reactive power of the network at night. However, this amount of use reactive power is limited. The basic equation for power-flow analysis is derived from the nodal analysis equations for the power system: For example, for a 3-bus system,

$$\begin{bmatrix} Y_{11} & Y_{12} & Y3 \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \tag{1}$$

$$I_i = Y_{i1}V_i + Y_{i2}(V_i - V_2) + Y_{i3}(V_i - V_3) = V_i\sum_{l=1}^{n} Y_{ij} - \sum_{j=2}^{n} Y_{ij}V_j \quad j \neq i \tag{2}$$

where Y_{ij} are the elements of the bus admittance matrix V_i are the terminal voltages, and I_i are the currents supplied at each terminal. The node equation at bus i can be written as;

$$I_i = \sum_{j=1}^{n} Y_{ij}V_j \tag{3}$$

relevance between per-unit real and reactive power injected to the system at bus i and the per-unit current injected into the system at that bus:

$$P_i + jQ_i = V_i I^*_i \tag{4}$$

where V_i is the per-unit voltage at the bus; I_i* - complex conjugate of the per-unit current injected at the bus; P_i and Q_i are per-unit real and reactive powers of power system.

$$I_i = \frac{P_i - jQ_i}{V_i^*} = V_i\sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij}V_j \quad j \neq 1 \tag{5}$$

Inductive and capacitive operations of DG were examined to reveal the effects the voltage of feeders. During the simulation, power factor was assumed as 0.98 and fixed for Araklı-II feeder which is shown in Figure 5.

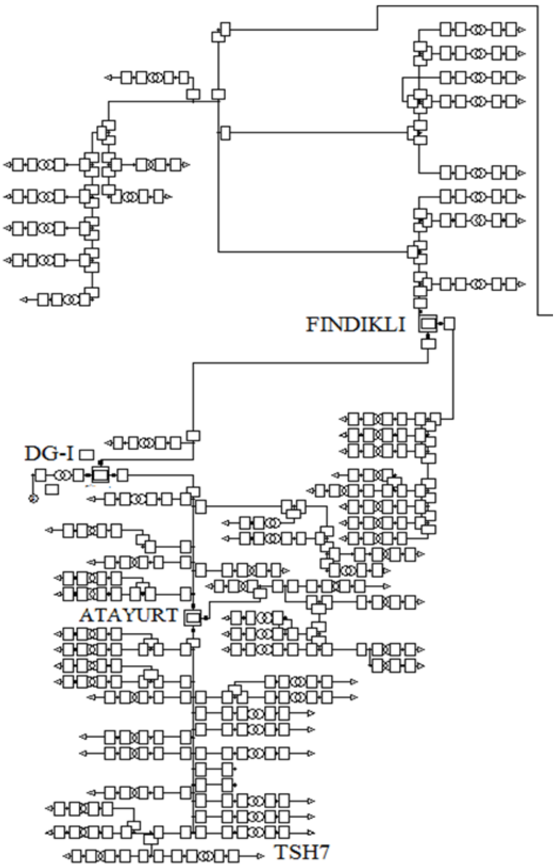

Fig. 5. Modeling of Araklı-II feeder using DIgSILENT power factory software

2.1. Voltage Profile During Night Time

Electric power demand from substation is minimum during at night. In the simulation, active power consumption is calculated as 24.5 MW at 13 January 2015 at 00:30. Consumption load values of distribution transformers are shared in proportion to the own nominal power values at feeders in the simulation. DG-I produced 6.7 MW real power and took 0.1 MVAr from network. DG-II produced 3.7 MW real power and take 0.3 MVAr from network. DGs are operated in sub-excited region at night to prevent increase of line voltage. All power values of DGs at night are shown in Table 3.

Table 3. Power values of DGs at night

DG Type	*P(MW)*	*Q(MVAr)*
DG-I	6.7	0.1
DG-II	3.7	0.3

The simulation results obtained according to this scenario are shown in Figure 6. The voltage increased at the terminal points connected to both DGs. For example, voltage of busbar rises by maximum 3% near the DG-I such as Fındıklı or Atayurt terminal.

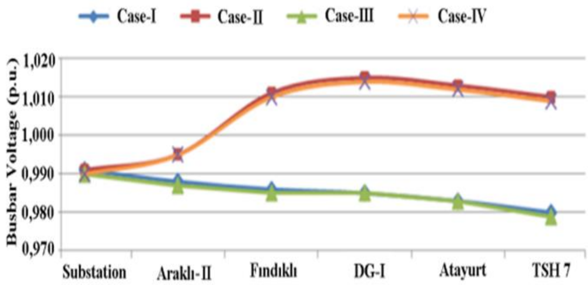

Fig. 6. Voltage profile for Araklı-II feeder at night

2.2. Voltage Profile During Peak Time

The peak power demand time of network was recorded on 29th of January 2015 at 17:30. The active power consumption is noted about 43 MW. The DGs are operated in over-excited region at peak time to prevent decrease of line voltage.

Table 4. Power values of DGs in peak time

DG	*P(MW)*	*Q(MVAr)*
DG-I	9.6	-0.4
DG-II	4.2	-0.7

2.3. Voltage Profile Estimation for Future

The average power consumption increase per year is about 5% for last decade in Turkey [10]. The peak power demand were calculated as 55 MW for the year 2020 and 70 MW for the year 2025 by using this rate. DGs are operated in over-excited region with same values in section 2.1. Terminals voltage level increased between 5% and 0.3%, approximately.

The line voltage decreases when the consumer loads increase. Adding a power transformer to the grid is a solution for this problem. However, DGs support the voltage profile and delivery power of the line in a positive way. For this reason, DGs may delay the investment to be made in this region. The voltage profile according to load estimates of 2020 and 2025 is given in Figure 7.

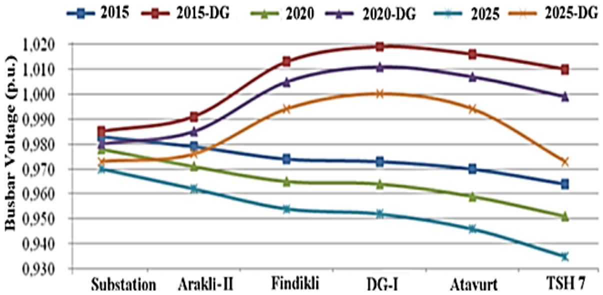

Fig. 7. Voltage profiles of Arakli-II feeder for 2015 and beyond

3. SHORT-CIRCUIT ANALYSIS

Short circuit current was occurred when two or more electrical point at different voltages contact over low impedance [11]. If it is assumed that the impedance does not change in the networks, the current value is found with the Equation 6 and 7 where;

- L : Network inductance
- R : Network resistance
- E : Maximum value of induced voltage
- V_a: Fault voltage
- I_a : Fault current
- Z_f : Fault impedance
- θ, ϕ: Phase angle
- a : Operator
- I_{max}: Maximum current value
- $I_{0,1,2}$: Current symmetrical components
- $Z_{0,1,2}$: Impedance symmetrical components

$$L\frac{di}{dt}+Ri=E_m\sin(\omega t+\theta) \quad (6)$$

$$i=I_m\sin(\omega t+\theta-\phi)-I_m\sin(\theta-\phi)e^{-Rt/L} \quad (7)$$

The short circuit current consists of AC and DC components. While the AC component is a continuous signal that varies according to the frequency, the dc component t '= L / R is a current that goes out according to the time constant.

$$i=I_m\sin\omega t+I_{dc}e^{-Rt/L} \quad (8)$$

In the phase-to-earth short circuit, the current value can be found with the help of the following equations with the help of symmetrical components.

$$\begin{vmatrix} I_0 \\ I_1 \\ I_2 \end{vmatrix}=\frac{1}{3}\begin{vmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{vmatrix}\begin{vmatrix} I_a \\ 0 \\ 0 \end{vmatrix}=\frac{1}{3}\begin{vmatrix} I_a \\ I_a \\ I_a \end{vmatrix} \quad (9)$$

The total phase a current for a line-to-ground fault equals three times the phase a positive sequence current.

$$I_0=I_1=I_2=\frac{1}{3}I_a \quad (10)$$

If the phase-to-ground short-circuit current is over the Z_F resistance, the short-circuit current value is;

$$3I_0Z_f=V_0+V_1+V_2=-I_0Z_0+(V_a-I_1Z_1)-I_2Z_2 \quad (11)$$

$$I_a=3I_0=\frac{3V_a}{(Z_1+Z_2+Z_0)+3Z_f} \quad (12)$$

In this simulation, single phase ground and three phase steady-state short circuit currents (Ik") were calculated per IEC60909 standard. Short-circuit faults were performed on high and medium voltage (MV) busbar of substation, and on some important connecting nodes at Araklı-II feeder.

3.1 Phase-to-Ground Short Circuit Analysis

Most of the short-circuit failures in medium voltage network is phase-to-ground [12]. The most important factor on the short-circuit current is the short-circuit power of grid and short-circuit impedance [13]. Although short circuit impedance is high in single-phase short-circuit and it is low in three-phase short-circuit. Short relative circuit voltage value (U_k %) of power transformers is shown in Table 5. Single-phase short-circuit current and effects of DGs on this current shown in Table 6. These currents values were investigated for all operation conditions when generator was producing maximum power.

DGs caused very little current rise at substation cabin. But they highly affected busbar and cabins which are close to them. It is observed that phase-to-ground short circuit fault current increased 13.5% at busbar which is close to DG-I and increased 1.21% at MV busbar on substation.

Table 5. Information of distribution transformers

Power (KVA)	Short-circuit Voltage (%)	X/R	Vector Group	Earth Resistance(Ω)
TR-A	9.12	20	YNyn0	20
TR-B	12.3	50	YNyn0	50
2500	6	6.17	Dyn11	-/0
2000	6	5.62	Dyn11	-/0
1600	6	5.55	Dyn11	-/0
1250	6	5.68	Dyn11	-/0
1000	6	5.63	Dyn11	-/0
800	6	5.42	Dyn11	-/0
630	4.5	4.14	Dyn11	-/0
400	4.5	3.53	Dyn11	-/0
250	4.5	3.05	Dyn11	-/0
160	4.5	2.64	Yzn11	-/0
100	4.5	2.08	Yzn11	-/0
50	4.5	1.49	Yzn11	-/0

3.2 Three-Phase Short Circuit Analysis

In electrical systems, three-phase short circuit current occurs maximum 5% of all short circuit failure [14]. This fault current is symmetrical and its value is very high [15]. It was observed that the three phase short-circuit currents of the bus bars decreases with the distance from substation. The effect of DGs on the three-phase short-circuit current is relatively low at the terminals near the substation. However, this fault current increase is very high in the terminals where the DGs are connected. At the end of analyses, it was determined that three-phase fault current increased 28.2% at terminal which is close to DG-I and 10.7% at substation terminals. Three-phase short circuit currents of Araklı- II feeder and effects of DGs shown in Table 7.

Table 6. Phase-to-Ground short circuit currents (kA)

Feeder	DG (No)	DG- I	Change (%)	DG-II	Change (%)	DG I-II	Change (%)
TM-HV	8.94	9.02	0.92	9.00	0.70	9.08	1.57
TM-MV	3.73	3.76	0.67	3.75	0.56	3.78	1.21
Araklı	2.89	2.99	3.18	2.91	0.52	3.00	3.59
Fındıklı	1.94	2.14	10.58	1.94	0.36	2.15	10.79
DG-I	1.78	2.02	13.29	1.79	0.34	2.02	13.46
Atayurt	1.04	1.12	6.99	1.05	0.19	1.12	7.18
TSH-7	0.36	0.37	2.23	0.36	0.00	0.37	2.23

Table 7. Three phase short circuit currents (kA)

Feeder	DG (No)	DG I	Change (%)	DG-II	Change (%)	DG I-II	Change (%)
TM-HV	8.90	9.03	1.44	9.00	1.09	9.12	2.44
TM-MV	10.59	11.24	6.13	11.08	4.62	11.73	10.75
Araklı	6.13	6.80	10.90	6.28	2.40	6.94	13.27
Fındıklı	2.85	3.52	23.56	2.88	0.95	3.55	24.44
DG-I	2.47	3.15	27.51	2.49	0.81	3.17	28.24
Atayurt	1.55	1.81	17.04	1.56	0.45	1.82	17.30
TSH-7	0.48	0.50	5.05	0.48	0.00	0.50	5.05

4. CONCLUSION

The effect of distributed generations on voltage profile, single-phase to ground and three-phase short circuit currents were investigated in this study. The following conclusions can be summary as;

- When distributed generations is operated in sub-excited region, voltage profile increase 3% at busbar which close to distributed generation -I but voltage decrease 0.1% at substation centers.
- When distributed generations is operated in over-excited region, voltage profile increase 5% at busbar which is close to distributed generation -I and 0.3% at substation centers.
- Voltage levels increase from 0.935 p.u. to 0.973 p.u. at end of Araklı-II feeder when distributed generations are operated in over-excited region voltage.
- By providing active power from distributed generations to the grid, power transformer-A loading decreased from 119% to 96% and power transformer-B loading decreased from 88% to 71%.
- When distributed generations operated, Araklı-II distribution line loading was reduced by 33%.
- Phase-to-ground short circuit fault current increase is 13.46% and three phase short circuit current increase obtained as 28.2% at busbar which is close to distributed generation-I. So, distributed generations is more effective in three-phase short circuit fault current then phase-to-ground short circuit fault current.
- Phase-to-ground short circuit fault current increases 1.2% and three phase short circuit fault current increases 10.7 % at substation centers.

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