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RESEARCH ARTICLE

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ANALYSIS OF SENSITIVITY OF EQUIPMENT TRIP DUE TO VOLTAGE SAG IN TRANSMISSION NETWORK CONNECTED WITH PHOTO-VOLTAIC PLANT

NAVITA KHATRI[1], JAYA SHARMA[2], DEEPAK RATHOD[3], NEHA MAITHIL[4]
[1-4]Department of Electrical Engineering, SVITS, Indore

ABSTRACT

The industrial as well as domestic consumer's equipments are sensitive to voltage sags due to use of power electronic devices. Most of this sensitive equipment includes computers, adjustable speed drives, induction motors etc. The aim of this paper is to analyze the frequency of sensitive equipment trip in presence of Photo-voltaic generation. The frequency of total number of voltage sags is evaluated and then frequency of sensitive equipment trip is evaluated considering CBEMA curve.

Keywords- Voltage sags, Sensitive equipment, Photo-voltaic, CBEMA curve, ITIC, Distributed generation (DG), Renewable Energy Sources (RES)

I. INTRODUCTION

The voltage sag is very common event under the umbrella of power quality. The literature suggests that voltage sags are prominent occurring percentage compare to other power quality event [1]. Many industries as well as commercial customers suffer heavy financial losses due to voltage sags. Many studies had been performed to evaluate techno-economical losses due to occurrence of voltage sags [2-6]. According to the Standard IEEE 1346 [7] voltage sag definition is "a decrease in rms voltage or current at the power frequency for durations of 0.5 cycles to 1 minute". The characterization of voltage sag is done in terms of its magnitude and time duration. The voltage sag waveform characterization is shown in Figure 1.Magnitude of voltage sag is the value of residual voltage during the event. Duration of sag is time for which the rms voltage stays below a voltage sag threshold. Many sensitive loads cannot discriminate between sag and a momentary interruption. The severity of the effects of voltage sags depends not only on the direct effects on the equipment concerned, but also importance of function carried out by the equipment. Modern manufacturing methods involve complex continuous industrial processes like textile mills, utilizing many devices acting together. A failure of one single device, in response to voltage sag, can stop the entire process. This may be one of the most serious and an expensive consequence of voltage sags

To present equipment sensitivity of IT industry a voltage tolerance curve or power acceptability curve are defined. The Computer Business Equipment Manufacturers Association (CBEMA) [8] developed sensitivity curve to set limits to the withstanding capabilities of computers during voltage sag in terms of magnitude and duration. The Information Technology industry council (ITIC) revised the CBEMA curve. The Figure 2 shows CBEMA and ITIC curve. Similarly curves of other sensitive equipment are derived by extensive survey

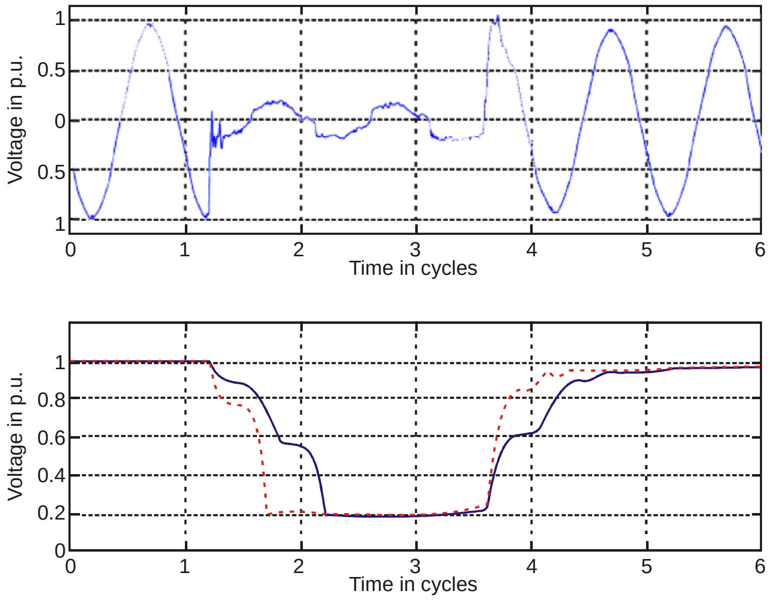

Figure 1: Voltage sags and its characteristics [7]

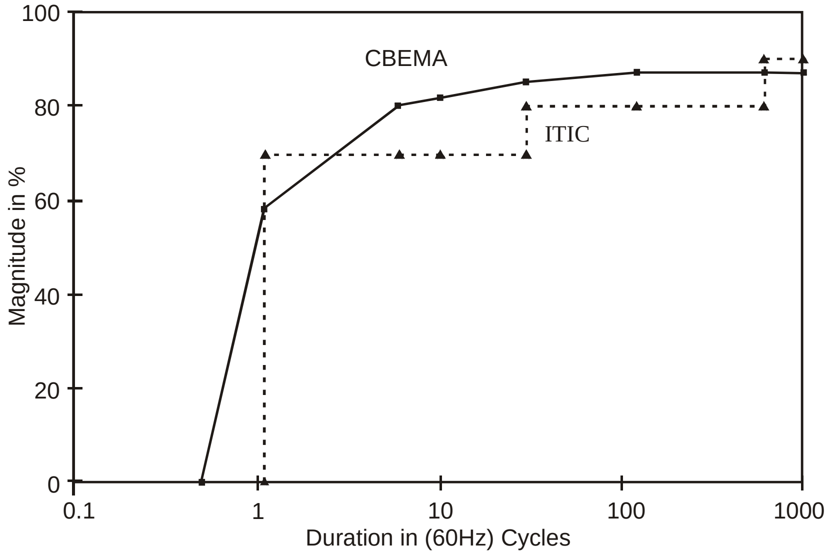

Figure 2: CBEMA and ITIC curve [8]

Present scenario, electric power systems are evolving from traditionally centralized bulk system with generation plants connected to the transmission network, to a future more decentralized system, with smaller generating units namely distributed generation (DG) connected to distribution networks or even directly to the power consumption. Besides a variety of technical and economic benefits to utilities, end users and the environment, the installation of DG in power systems also raises challenges to utilities in various aspects on network planning, design and operation. The DG challenges to network operation are due to the fact that the distribution system is traditionally designed with single energy source and the presence of DG changes system frequency power flows in either steady states or transient states. Among number of operational issues caused by DG involvement, impacts on power quality have been of great concern to utilities. Regarding the problems of voltage sag, characteristics of voltage sags in networks caused by faults are highly influenced by system's short-circuit power flowing through the fault as well as the configuration of protection system. All these aspects are also affected by the presence of DGs. Many researchers exploring impacts of DG on short-circuit and voltage sags performance in a transmission and distribution network [9-13]. By considering current research trend this work tries to find number of voltage sags in transmission network considering Photo- voltaic generation at various observation buses. The numbers of sensitive equipment trips are found with the help of CBEMA curve. The impact on number of sensitive equipment is shown in sub-transmission level with presence of photo-voltaic generation.

II. Photovoltaic System

The photo-voltaic (PVs) plants are most commonly used renewable energy sources (RES) for electric power generation due to numerous advantages like noiseless operation, modular expansion. Their application in power generation field is going to increase in near future [14-15]. Figure 3 shows the schematic diagram of an inverter for a small PV grid connected system. The main components of PV system includes

- Maximum power point tracking (MPPT) circuit
- Optional energy storage element, usually a capacitor (and/or batteries)
- An AC inverter (DC to AC)
- An Isolation transformer to prevent DC from being injected into the power system

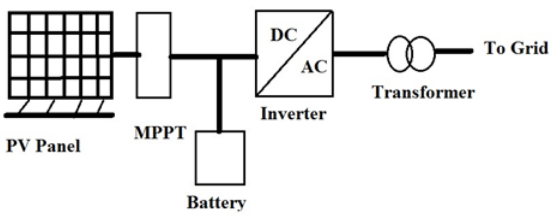

Figure 3: Schematic Diagram of a PV inverter for Grid Connected Operation.

When photo-voltaic system is connected to a network, modeling of PV plant is required for short circuit studies. The equivalent aggregated inverter will not contribute to the system short circuit current. So the inverter equivalent impedance is considered to be 999 pu. Inverters short-circuit ratio Ksc lies between1.1to 1.5[14-15].

III. Voltage Sag Methodology

For the calculation of voltage sag magnitude, load flow analysis is performed to get pre-fault voltage. In load flow analysis photo-voltaic is also included to get modified pre-fault voltages. In addition, various driving point and transfer impedances are calculated using Zbus building algorithm including photo-voltaic.

Now let us assume fault position is moving along the line connecting bus m-n. Let us consider fault occurring at position p which is λ distance from bus m. The parameter λ varies 0 to 1 as a fault position moves from bus m to n [16-19].

$$\lambda = \frac{L_{mp}}{L_{mn}} \quad (1)$$

The driving point impedance s and the transfer impedances and the transfer impedances of three sequence circuit can be expressed in terms of the sequence impedances. The sequence transfer impedance between the sensitive load bus k and fault position p can be expressed as

$$z_{kp}^{0} = (1-\lambda)z_{km}^{0} + \lambda z_{kn}^{0} \quad (2)$$

$$z_{kp}^{1} = (1-\lambda)z_{km}^{1} + \lambda z_{kn}^{1} \quad (3)$$

$$z_{kp}^{2} = (1-\lambda)z_{km}^{2} + \lambda z_{kn}^{2} \quad (4)$$

The pre-fault voltage at fault position p is expressed as follows

$$V_p^{pf} = (1-\lambda)V_m^{pf} + \lambda V_n^{pf} \quad (5)$$

Single line to ground (SLGF)

When an SLGF occur at phase A, the residual phase voltages at bus k can be expressed [16-19] as

$$V_A^f = V_A^{pf} - \frac{Z_{kp}^0 + Z_{kp}^1 + Z_{kp}^2}{Z_{pp}^0 + Z_{pp}^1 + Z_{pp}^2} V_p^{pf} \quad (6)$$

$$V_B^f = a^2 V_A^{pf} - \frac{Z_{kp}^0 + a^2 Z_{kp}^1 + a Z_{kp}^2}{Z_{pp}^0 + Z_{pp}^1 + Z_{pp}^2} V_p^{pf} \quad (7)$$

$$V_C^f = a V_A^{pf} - \frac{Z_{kp}^0 + a Z_{kp}^1 + a^2 Z_{kp}^2}{Z_{pp}^0 + Z_{pp}^1 + Z_{pp}^2} V_p^{pf} \quad (8)$$

Line to Line fault (LLF)

When an LLF occur between phase B and C, the residual phase voltages at bus k can be expressed as [16-19]

$$V_A^f = V_A^{pf} - \frac{Z_{kp}^1 - Z_{kp}^2}{Z_{pp}^1 + Z_{pp}^2} V_p^{pf} \quad (9)$$

$$V_B^f = a^2 V_A^{pf} - \frac{a^2 Z_{kp}^1 - a Z_{kp}^2}{Z_{pp}^1 + Z_{pp}^2} V_p^{pf} \quad (10)$$

$$V_C^f = a V_A^{pf} - \frac{a Z_{kp}^1 - a^2 Z_{kp}^2}{Z_{pp}^1 + Z_{pp}^2} V_p^{pf} \quad (11)$$

Double Line to Ground Fault (DLGF)

When a DLGF occur at phases B and C involving ground the residual phase voltages at bus K is expressed as [16-19].

$$V_A^f = V_A^{pf} - \frac{(Z_{kp}^1 - Z_{kp}^0)Z_{kk}^2 + (Z_{kp}^1 - Z_{kp}^2)Z_{kk}^0}{Z_{pp}^0 Z_{pp}^1 + Z_{pp}^1 Z_{pp}^2 + Z_{pp}^2 Z_{pp}^0} V_p^{pf} \quad \textbf{(12)}$$

$$V_A^f = a^2 V_A^{pf} - \frac{(a^2 Z_{kp}^1 - Z_{kp}^0)Z_{kk}^2 + (a^2 Z_{kp}^1 - a Z_{kp}^2)Z_{kk}^0}{Z_{pp}^0 Z_{pp}^1 + Z_{pp}^1 Z_{pp}^2 + Z_{pp}^2 Z_{pp}^0} V_p^{pf} \quad \textbf{(13)}$$

$$V_A^f = a V_A^{pf} - \frac{(a Z_{kp}^1 - Z_{kp}^0)Z_{kk}^2 + (a Z_{kp}^1 - a^2 Z_{kp}^2)Z_{kk}^0}{Z_{pp}^0 Z_{pp}^1 + Z_{pp}^1 Z_{pp}^2 + Z_{pp}^2 Z_{pp}^0} V_p^{pf} \quad \textbf{(14)}$$

Three Phase Fault (3PF)

In balanced fault only positive sequence matrix is required. When a 3-ph fault occurs, the residual voltage at bus k can be expressed as [16-19]

$$V_k^f = V_k^{pf} - \frac{Z_{kp}^1}{Z_{pp}^1} V_p^{pf} \quad \textbf{(15)}$$

IV Analysis of Number of Sensitive Equipment Trip

The frequency of voltage sags at particular threshold value is very important to find. But simultaneously it is necessary to find frequency of sensitive equipment trip due to voltage sag occurring on the observation bus. The number of sensitive equipment trip and their effect when DG connected in the system is investigated through new CBEMA curve [20]. The table I summarizes voltage sag condition for sensitive equipment.

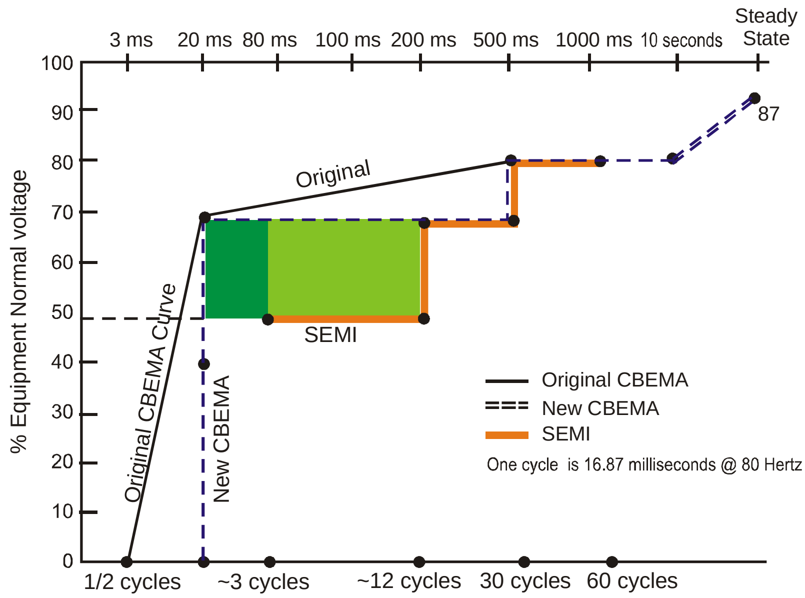

Figure 5: New CBEMA curve [20]

Table I: Voltage sag condition for sensitive equipment trip

S. No.	Voltage sag magnitude in pu	Time duration
1	0.7	20-500ms
2	0.8	500ms-10s

Table II :Failure rate for buses and lines

Type of fault	Bus failure rate (Event/Year)	Line Failure Rate (Event/100 km/year)
SLGF	0.064	2.00
LLF	0.004	0.125
DLGF	0.008	0.300
3PF	0.003	0.100

V. Result and Discussion

(a) Case study: The voltage sags are evaluated for IEEE 30 bus reliability test system shown in Figure 4 consists of five generating units, 30 buses interconnected by 37 lines, and 4 transformers. The failure rate for buses and line is given in table II. The positive, negative and zero sequence internal impedances of all generators are j0.3, j0.2 and j0.05 respectively. The system data are available from [21].

The solar photo-voltaic plant of capacity of 10 MW, 12.5 KV each is considered to be connected at various buses. For increase in penetration level, numbers of solar units are increased at various buses. The modeling of PV plant can be done as current source having resistance of 999 p.u. The operation of PV plant considered to be under constant power factor control mode. The PV generator is modeled as P-Q bus with constant the power factor of 0.95 for load flow study. Results are obtained for different penetration levels. The case study is shown in table III.

Table III: Case study with various penetration level of PV system

Case 1	Without DG
Case 2	PV system connected at Bus 7 with 3.3 % penetration level
Case 3	PV system connected at Bus 7 and 23 with 6.6 % penetration level
Case 4	PV system connected at Bus 7, 19 and 23 with 10 % penetration level
Case 5	PV system connected at bus 7,14,19 and 29 with 13.3% penetration level

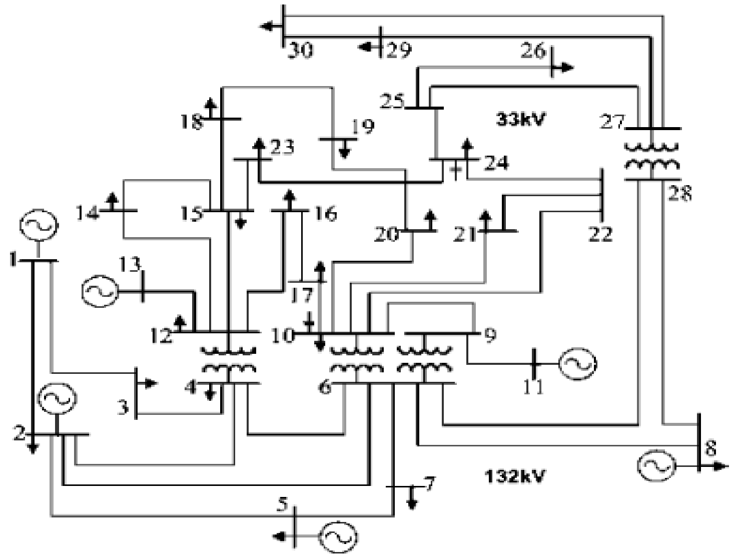

Figure 4: Single-line diagram of the IEEE-30 bus system[21].

(a) Frequency of equipment sensitivity considering photo-voltaic plant

The equipment sensitivity for Sensitive equipment in transmission system connected with PV system is investigated for different penetration level for observation bus 7, 18 and 24. The results are shown in Table IV, V and IV. It can be seen that transmission system without PV has higher frequency of SE trip. When PV system is connected to transmission network frequency of SE trip reduces approximately 88% for observation bus 7, 21 % for bus 18 and 72% for bus 24. A large reduction is observed in frequency of SE trip. Hence with inclusion of PV reduces number of SE trip. If we compare different penetration level of PVs in transmission system, it is observed with increase in penetration upto 10% reduces frequency of SE trip as well as number of voltage sags. But above 10% penetration level frequency of SE trip starts increasing.

Table IV: Frequency of SE trip at Observation Bus 7 with PV system

CASE STUDY	FREQUENCY OF SE TRIP	FREQUENCY OF TOTAL NO OF VOLTAGE SAGS
Case 1(Without DG)	101.4611	183.6217
Case 2	12.2045	22.23154
Case 3	12.070	22.004
Case 4	11.906	21.860
Case 5	12.017	21.733

Table V: Frequency of SE trip at Observation Bus 18 with PV system

CASE STUDY	FREQUENCY OF SE TRIP	FREQUENCY OF TOTAL NO OF VOLTAGE SAGS
Case 1(Without DG)	22.51	183.5523
Case 2	17.645	26.0058

Case 3	16.482	25.5646
Case 4	15.411	24.82515
Case 5	15.6943	24.836

Table VI: Frequency of SE trip at Observation Bus 24 with PV system

CASE STUDY	FREQUENCY OF SE TRIP	FREQUENCY OF TOTAL NO OF VOLTAGE SAGS
Case 1(Without DG)	66.7412	187.8448
Case 2	18.6312	28.4851
Case 3	17.3124	28.278
Case 4	17.0266	27.8554
Case 5	17.3414	28.1914

VI Conclusion

This paper analyzes the number of sensitive equipment trip with presence of photo-Voltaic plant connected with transmission line. The penetration of photo-voltaic also increased in transmission network. This conclusion can be drawn from present study that with inclusion of photo-voltaic plant in transmission network reduces the frequency of sensitive equipment trip. This results into reduction in technical and financial losses occurring due to sensitive equipment trip.

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