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Preliminary communication

A COMPARATIVE STUDY ON COMMON POWER FLOW TECHNIQUES IN THE POWER DISTRIBUTION SYSTEM OF THE TEHRAN METRO

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Abstract: Overall, a power-flow study is a steady-state assessment whose goal is to specify the currents, voltages, and real and reactive flows in a power system under a given load conditions. This paper presents a comparison of common power flow techniques in the Tehran metro power distribution system at the presence of non-linear loads. Moreover, a modelling, simulation and analysis of this power distribution system is implemented with the Electrical Transient Analyser Program (ETAP) software. In this assessment, common power flow techniques including the Newton-Raphson (NR), Fast Decoupled (FD), and Accelerated Gauss-Seidel (AGS) techniques are provided and compared. The obtained results (total generation, loading, demand, system losses, and critical report of the power flow) are analysed. In this paper, we focus on the detailed assessment and monitoring by using the most modern ETAP software, which performs numerical calculations of a large integrated power system with fabulous speed and also generates output reports. The capability and effectiveness of the power flow analysis are demonstrated according to the simulation results obtained with ETAP by applying it to the power distribution system of the Tehran metro. In developing countries such as Iran, off-line modelling and simulation of power grids by a powerful software are beneficial and helpful for the best usage of the electrical energy.

Keywords: ETAP; modelling; Power Flow Assessment; simulation; Tehran metro

1 INTRODUCTION

1.1 Background

The purpose of power flow studies is to plan ahead and account for various hypothetical situations. For instance, if a transmission line is to be taken off line for maintenance, the question is whether the remaining lines in the system can handle the required loads without exceeding their rated values. Power flow is one of the most important tools utilized by electrical experts for the design, planning, control, and analysis needed to determine and specify the best operation for power distribution systems and the exchange of power between utility companies. In the past few years, electrical engineers have been dealing with power system studies by using new software tools. Recent advances in electrical engineering sciences have brought a revolution in the field of electrical engineering after the development of powerful computer-based software [1-4]. A load flow assessment method might take a long time, and hence prevent the achievement of an accurate result for a power flow solution due to continuous changes in power generation and demand. The essential data achieved from a load flow study is the magnitude and phase angle of the voltage at every feeder and bus, and the real and reactive power flowing in every line [5, 6]. Commercial power systems are usually too complex to allow handling solutions for the power flow. Large-scale digital computers have replaced analogous methods with numerical solutions. Moreover, in order for the power flow study to function, computer programs perform related calculations such as short-circuit fault assessment, stability studies with a focus on the transient and steady-state, unit commitment and economic dispatch [7]. Maintaining a high level of system security is one of the more important aspects of power systems that should be noted, as well as the economic operation of these systems [8, 9].

1.2 Literature Review

In recent years, many researchers have proposed different approaches for the analysis, simulation and modelling in power systems and metro structures. Some recently published papers and literature reviews can be found in [10-14]; the most important factors of metro tunnel safety and the importance of safety and security needed to enable the existence of more comfortable services in metro tunnel and subway stations is explained in [15]; in the reference [16], the criteria and rules for the design of a metro path are discussed; in the paper [17], the authors presented a review of a probabilistic load flow in power systems; the reference [18] deals with the analytical methodology for the assessment of a smart monitoring impact on a future electric power distribution system. In the papers [19, 20], new prediction model based on a new feature selection and hybrid prediction engine are introduced.

The Newton-Raphson (NR) power flow, with a consideration of the fuzzy load and in the presence of distributed generations in a distribution network, is presented in [21]. The paper [22] uses a new algorithm for the optimal sizing and sitting of distributed generation in a power system. The summary explanation of the nonlinear of load flow problems is described in the reference [23]. The references [24, 25] propose a novel method to deal with energy minimization; and finally in the paper [26], wavelet decomposition combined with an adaptive neuro-fuzzy inference system is used for short-term wind power forecasting. In the reference [27], by using a modified breadth-first search strategy, the improvement of a backward/forward sweep load-flow approach is presented. The goal of the paper [28] is to specify the optimal grid switching condition of minimum losses, with the precondition of keeping the stable voltages on all buses.

1.3 Motivation and Main Contribution

In this paper, the research team focuses on the effective usage of the ETAP software for the load flow assessment and modelling of the electrical power network of the Tehran metro. The results comprise large power distribution systems emanating from high voltage (H.V.), medium voltage (M.V.), and low voltage (L.V.) networks, equipment and loads; the data used for the assessment objective are in the form of one line diagrams of the complete and actual power grid of the Tehran metro starting from HVS and the power transformer at the grid up to the loads. The ratings of all components of the power system network are taken as they actually exist. Moreover, the transformers, load switch (L.S.) and circuit breakers (C.B.), conductor's cables, distribution system and DC components are also simulated according to the actual ratings by the ETAP, and this innovative concept deals with 63 kV, 20 kV, 0.75 kV and 0.4 kV network simulations with the ETAP software.

1.4 Paper Structure

The remainder of this paper is organized as follows: Section 2 introduces the fundamental theories of the proposed method. Section 3 describes a case study analysis approach to the power distribution system of the Tehran metro in detail. In Section 4, the prediction results are given. The conclusions are presented in Section 5.

2 MATERIALS AND METHOD

In this section, three common power flow methods are explained.

2.1 Bus Classifications

According to the references [29-32], the feeder bus is a point or node where one or several generators, transmission lines, and loads are connected. It can be said that generally, in every power system analysis, each feeder bus is associated with four quantities: active power (P), reactive power (Q), voltage magnitude ($|V|$), and voltage phase angle (δ). Furthermore, feeders are divided into three categories: 1) slack bus, 2) generator (PV) bus, and 3) load (PQ) bus. Those three categories are shown in Tab. 1.

Table 1 Bus classification

Type of Bus	Variables			
	P	Q	V	δ
Slack	Unknown	Unknown	Known	Known
(PV)	Known	Unknown	Known	Unknown
(PQ)	Known	Known	Unknown	Unknown

2.2 Power Flow Calculation Methods

In the last few decades, for solving load flow analysis problems, several numerical assessment methods have been proposed. It can be said that the most commonly used iterative methods are the Gauss-Seidel (GS), the Fast-Decoupled (FD), and the FD methods [5, 33]. According to the reference [5], when performing load flow assessment, the first step is to form the Y-bus admittance using the transmission line and the transformer input data. The nodal formula for a study of the power system network using the Y-bus can be given as follows:

$$I = Y_{Bus}V \tag{1}$$

The nodal formula can be expressed in a generalized form for a n bus system as follows:

$$I_i = \sum_{j=1}^{n} Y_{ij}V_j; \text{ for } i = 1, 2, 3, \dots, n \tag{2}$$

And the complex power and the current delivered to bus i are given by the following formula:

$$P_i + jQ_i = V_i I_i^* \tag{3}$$
$$I_i = \frac{P_i - jQ_i}{V_i^*} \tag{4}$$

Replacing for I_i in terms of P_i and Q_i, the following formula is given as:

$$\frac{P_i - jQ_i}{V_i^*} = V_i \sum_{j=1}^{n} Y_{ij} - \sum_{j=1}^{n} Y_{ij} V_j ; \ j \neq i \tag{5}$$

On the other hand, according to the reference [34], a complex power injection of the system is given by the following formula:

$$S_i = S_{Gi} - S_{Di} = \text{Generation} - \text{Load} \tag{6}$$
$$S_i = \sum_{k}^{n} S_{ik} \tag{7}$$

where in the Eqs. (6) and (7): $k = 1, 2,\dots, n$; $i = 1, 2,\dots, n$. Similarly, the phasor of current injections is given by the following formula:

$$I_i = I_{Gi} - I_{Di} = \sum_{k}^{n} Y_{ik} V_{ik} \tag{8}$$
$$S_i = V_i I_i^* = V_i \sum_{k}^{n} Y_{ik}^* V_k^* \tag{9}$$
$$S_i = \sum_{k}^{n} |V_i||V_k| e^{j\delta ik} (G_{ik} - jB_{ik}) \tag{10}$$

where: $V_k = |V_k|e^{i\delta ik}$; $\delta_{ik} = \delta_i - \delta_k$; $Y_{ik} = G_{ik} + jB_{ik}$

Breaking down the complexity of power flow formulation into real and imaginary parts is given by the following formula:

$$S_i = P_i + jQ_i = \sum_{k}^{n} |V_i||V_k| e^{j\delta ik}(G_{ik} - jB_{ik}) \tag{11}$$
$$P_i = \sum_{k}^{n} |V_i||V_k| [G_{ik}\cos(\delta_{ik}) + B_{ik}\sin(\delta_{ik})] \tag{12}$$
$$Q_i = \sum_{k}^{n} |V_i||V_k| [G_{ik}\cos(\delta_{ik}) - B_{ik}\sin(\delta_{ik})] \tag{13}$$

These Eqs. (11), (12), and (13) utilize iterative techniques to solve power flow problems. Therefore, they are necessary to review the general forms of these various solution methods: NR, FD and Accelerated Gauss-Seidel (AGS) power flow.

2.3.1 Newton-Raphson Method

The NR method iteratively solves and formulates the following power flow equation:

$$\begin{vmatrix}\Delta P\\ \Delta Q\end{vmatrix} = \begin{vmatrix}J1 & J2\\ J3 & J4\end{vmatrix}\begin{vmatrix}\Delta\delta\\ \Delta V\end{vmatrix} \tag{14}$$

where in the Eq. (14), $J1$, $J2$, $J3$ and $J4$ are the Jacobean matrix elements. P and Q are the specified feeder real and reactive power mismatch vectors between the calculated value and the specified value, respectively; ΔV and $\Delta\delta$ represent the voltage magnitude of the feeder bus and angle vectors in an incremental form; besides, the elements from $J1$ to $J4$ are named Jacobean matrices [30, 32, 35, 36].

2.3.2 Fast-Decoupled Method

The FD method originated from the NR method. It takes in the fact that a small variation in the voltage magnitude of the feeder bus does not extremely change the real power at the feeder bus, and also, for a small variation in the phase angle of the feeder bus voltage, the reactive power does not vary too much. Therefore, the equation of the power flow from the NR method can be simplified into two separate decoupled sets of power formulas, which according to the references [30, 32, 35, 36] can be solved iteratively:

$$\begin{aligned}|\Delta P| &= |J1||\Delta\delta|\\ |\Delta Q| &= |J1||\Delta V|\end{aligned} \tag{15}$$

It can be said that compared to the N-R method, the FD method reduces the storage of computer memory by almost half. It also solves the power flow formulas by taking substantially less computer time than that required by the NR method, due to the fact that Jacobean matrices are constant [30, 32, 35, 36].

2.3.3 Accelerated Gauss-Seidel Method

Based on the equation of the system nodal voltage:

$$|I| = |Y_{Bus}||V| \tag{16}$$

The AGS method derives the following power flow formula and solves it iteratively:

$$|P + jQ| = |V^T||Y_{Bus}^* V^*| \tag{17}$$

where in the Eq. (17), P and Q are the specified bus real and reactive power vectors, V is the voltage vector of the feeder bus; Y_{Bus} is the admittance matrix of the system. Y_{Bus}^* and V^* are the conjugates of Y_{Bus} and V, respectively. V^T is the transpose of V [30, 32, 35, 36].

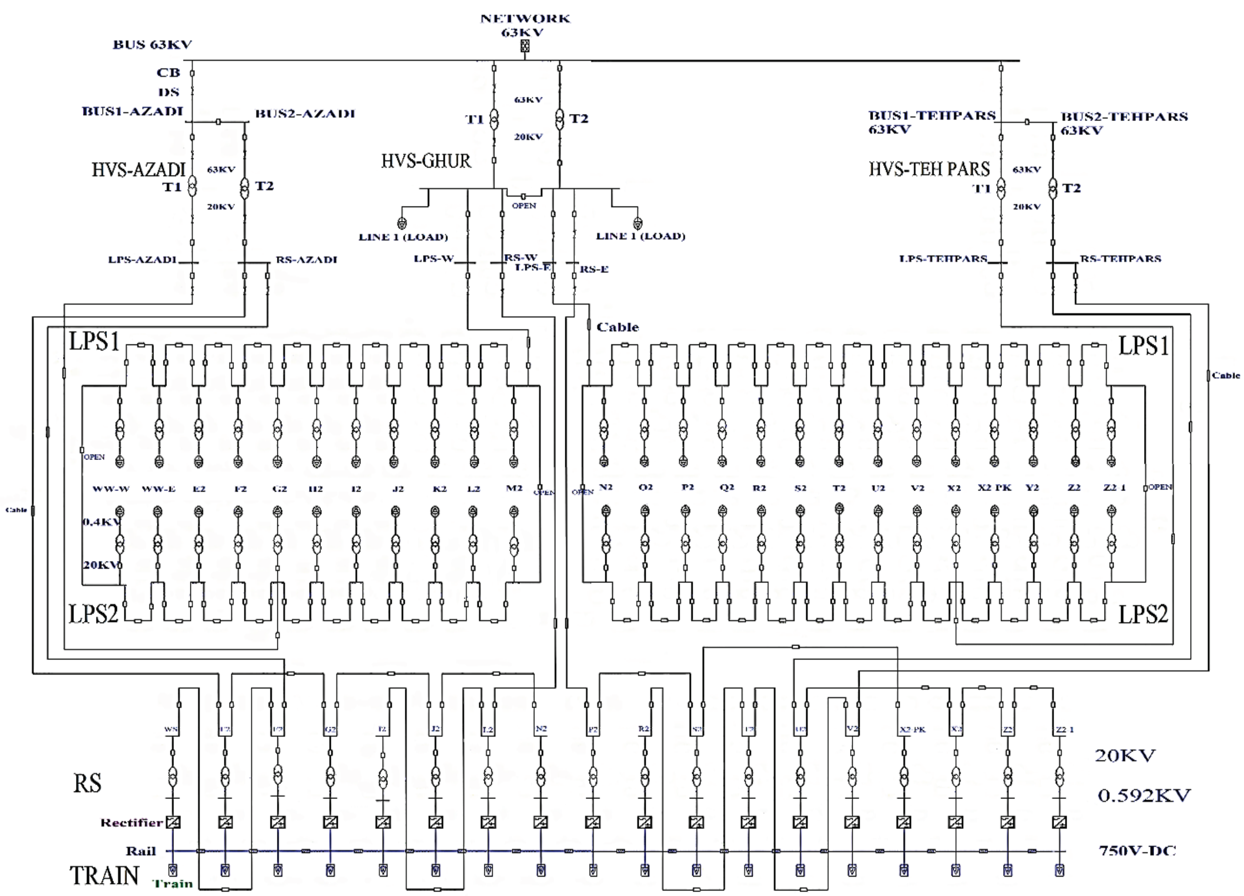

Figure 1 Single line diagram of the Tehran metro power distribution system in the form of ETAP

Table 2 LPS information data

Station	LPS	kW·h	kVAr·h	% P.F
WWW	LPS1	13210	12610	0.7233555
	LPS2	88820	58220	0.8363717
WWE	LPS1	104430	46830	0.9125093
	LPS2	79240	59440	0.8011232
E2	LPS1	134450	87650	0.8377593
	LPS2	164460	105100	0.8427737
F2	LPS1	75070	62450	0.7687251
	LPS2	79880	46860	0.8626003
G2	LPS1	82290	52870	0.8413779
	LPS2	48610	43880	0.7428379
H2	LPS1	98420	59290	0.8568776
	LPS2	65630	42300	0.8398448
I2	LPS1	70240	63610	0.7410854
	LPS2	66650	54620	0.7733361
J2	LPS1	77460	71430	0.7350218
	LPS2	50470	49840	0.7113282
K2	LPS1	81080	100250	0.6263911
	LPS2	39090	54660	0.5812381
L2	LPS1	63610	90670	0.5745531
	LPS2	85820	96680	0.6640755
M2	LPS1	104430	88290	0.7638856
	LPS2	104000	87100	0.7700215
N2	LPS1	28700	36100	0.6204821
	LPS2	123500	90100	0.8083965
O2	LPS1	55220	57500	0.6919053
	LPS2	121230	94300	0.7895626
P2	LPS1	135640	80500	0.8601678
	LPS2	51650	23300	0.9107287
Q2	LPS1	36460	27100	0.8010550
	LPS2	22470	34900	0.5412459
R2	LPS1	145280	108700	0.8007934
	LPS2	38490	24100	0.8479983
S2	LPS1	159100	114610	0.8112439
	LPS2	41300	39100	0.7278902
T2	LPS1	156100	112100	0.8118303
	LPS2	28210	20500	0.8102244
U2	LPS1	154100	115900	0.7996264
	LPS2	36000	32500	0.7432941
V2	LPS1	165500	119410	0.8111439
	LPS2	6620	8410	0.6178215
X2	LPS1	53300	26100	0.8984435
	LPS2	143610	40500	0.9626290
Y2	LPS1	143252	93292	0.8380018
	LPS2	44735	7475	0.9863348
Z2	LPS1	58049	20251	0.9446808
	LPS2	120174	54718	0.9101126
Z2-1	LPS1	24266	43813	0.4842675
	LPS2	21245	24950	0.6485155
X2-PK	LPS1	78410	36810	0.9052369
	LPS2	44420	26010	0.8629317

3 CASE STUDY

According to the reference [37], the line 2 of the Tehran metro is supplied from three high voltage substations (HVS) and consists of 154 main feeders. All HVSs in the power network of the Tehran metro comprise 63/20 kV and a gas insulated substation (GIS) type. Each station of the Tehran metro has two lighting and power substations (LPS). The LPSs supply electric power for the equipment and loads. The LPS is located at each substation platform. The rectifier substation (RS) converts AC to DC power to supply electrical energy for the traction motors of trains. Most stations on line 2 of the Tehran metro have one RS. Each RS is capable to convert 20 kV (AC) to 750 V (DC) using diode rectifiers. A single line diagram of the Tehran metro power distribution system in the form of ETAP is displayed in Fig. 1.

As shown in Fig. 1, HVSs are located at the top, LPSs and loads at the middle, and RSs and loads at the bottom. According to the monthly report (August 2017) from the Tehran metro power distribution unit, the total consumption for LPSs and RSs (active and reactive) are measured, and that informational data are presented in Tab. 2 and Tab. 3, respectively.

Table 3 RS information data

Station - RS	kW·h	kVAr·h	% P.F
WW	38020	7020	0.9834531
E2	258020	35020	0.9909234
F2	305030	51030	0.9863063
G2	365040	69030	0.9825968
I2	389050	69040	0.9846302
J2	313060	55050	0.9849100
L2	408070	72060	0.9847835
N2	291080	46070	0.9877354
P2	365090	62020	0.9858781
R2	292100	51010	0.9850876
S2	292500	47010	0.9873774
T2	222100	32030	0.9897701
U2	198020	27000	0.9901485
V2	195030	23050	0.9931157
X2	236040	30010	0.9920170
Y2	198050	51020	0.968391
Z2	206000	51030	0.9709646
Z2-1	217010	55000	0.9704049

For the implementation of this simulation, the values used to compare the three methods of load flow are shown in Tab. 4.

Table 4 The values of power flow methods

Method	Max Iteration	Precision	Accel. Factor
NR	10	0,0001	-
FD	99	0,0001	-
AGS	2000	0,00001	1,45

4 RESULTS AND ANALYSIS OF THE POWER FLOW

Tab. 5 shows the summary report of branch losses (Max. Loading) in the power distribution grid of the line 2 of the Tehran metro.

Table 5 Branch losses summary report (Max Loading)

Method	Losses Branch (Transformers, Cables)	
	kW (*P*)	kVAr (*Q*)
NR	1494.61	18168.20
FD	1494.62	18168.22
AGS	1494.61	18168.21

As it can be seen from Tab. 5, the results of all three methods are very close together.

As it can be seen, the results of these three load flow methods are almost exactly the same; hence, due to the similarity of the results in each of the three load flow simulations, the critical reports of the NR load flow are illustrated in Fig. 2 and 3 respectively. Fig. 2 shows the amount of under voltage (kV) in different distribution transformers. Fig. 3 shows the percentage of overload on transformers. The marginal and critical voltage drop and overload standard set by utility are 2% and 5% respectively, and here they are significantly violated. The summary of the total generation, loading and demand for the maximum loading of the case study are shown in Tab. 6.

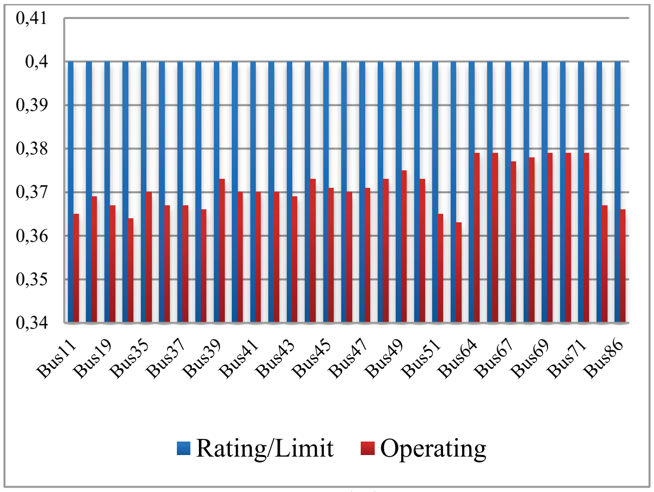

Figure 2 Voltage drop (kV) on the buses

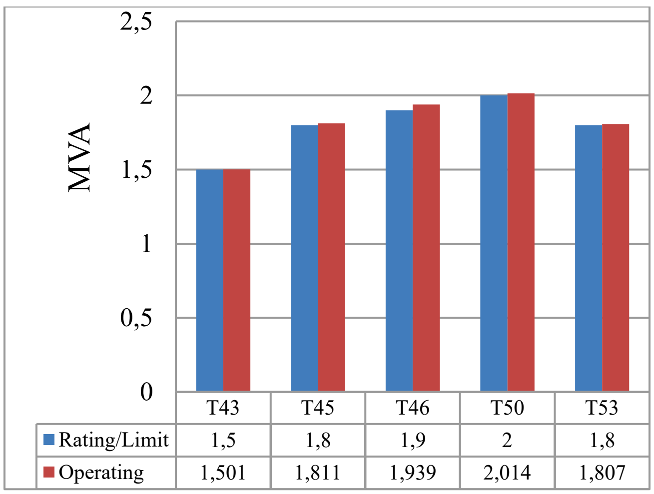

Figure 3 Overload on transformer

Table 6 Summary of total generation, loading and demand (Max. Loading)

Type	MW (P)	MVAr (Q)	MVA (S)	% P.F
Source	97.824	83.84	128.345	73.22 Lagging
Total Demand	97.824	83.084	128.345	76.22 Lagging
Total Motor Load	86.764	58.037	104.385	83.12 Lagging
Total Static load	9.566	6.878	11.782	81.19 Leading
Apparent Losses	1.495	18.168	-	-

5 CONCLUSION

In this paper, a case study of the modelling, simulation and power flow analysis of the actual power distribution system of the Tehran metro (Line 2) in the presence of non-linear loads by using the ETAP was implemented. Furthermore, a comparison of three common power flow techniques was presented. The theoretical and practical approaches of load flow have been learned, compared, and applied to solve the given tasks. The results of power flow assessment (total generation, loading, demand, and power losses) were obtained and analysed. The numerical methods of the power flow (Newton-Raphson, Fast-Decoupled, and Accelerated- Gauss-Seidel) were compared. Moreover, a power flow based simulation using the ETAP were developed to find the optimum location of the distribution system unit for a load profile improvement and the minimization of power losses in the test distribution system. By using a powerful software such as ETAP for speed performance and computational accuracy is very practical and helpful, and it also offers a better view of the power network for analysis. In a developing country such as Iran, it is highly beneficial that off-line modelling includes the active and reactive power flows, current flow in every branch, PF correction, reliability analysis, etc. of a large electrical power system. Additionally, understanding the best way of the power flow is economical, and therefore it can be a hot topic for future studies of the power distribution system.

Nomenclature

AC	Alternating current
B	Susceptance (Ω^{-1})
DC	Direct current
G	Conductance (Ω^{-1})
I	Current (A)
I^*	Conjugate of I
J	Jacobian matrix
n	Number of branch (i, k)
P	Active power (kW)
Q	Reactive power (kVAr)
PV	Generator bus
PQ	Load bus
S	Apparent power (kVA)
V	Voltage (V)
V^*	Conjugate of V
V^T	Transpose of V
Vi	Voltage at node i (V)
$\lvert V \rvert$	Voltage Magnitude
Y	Admittance (Ω^{-1})
Y_{Bus}^*	Conjugate of Y_{Bus}
i, j and k	Indices of buses
δ	Phase angle of voltage (degree, rad)
Δ	Mismatch
P.U	Per unit
kVA	Kilo volt ampere
kVAr	Kilo var

List of abbreviations

RS	Rectifier Substation
LPS	Lighting and Power Substation
HVS	High Voltage Substation
P.F	Power Factor
GIS	Gas Insulated Substation

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