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A LOAD FLOW COMPARATIVE ANALYSIS USING COMMERCIAL POWER SYSTEMS TOOLS

BY

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Abstract. The paper proposes a comparative analysis of the load flow computation for high voltage (HV) distribution networks. Power flow study has great importance in planning during the expansion of power system as well as for determining the best operational conditions. For this purpose, four of the most used commercial power systems analysis software packages were tested. The first directions aim to compute the active and reactive power flow with the active power losses, and secondly the bus voltage and the lines loading. Both of the aforementioned goals were solved using the Newton Raphson method. Having the real bus data, provided by the SCADA systems, the objective of the paper is the evaluation of each studied software with respect to the output results. For emphasize the results a real HV distribution network was used. The results from all proposed tools were compared and some conclusions are drawn.

Keywords: load flow; distribution networks; high voltage.

1. Introduction

Power system analysis modelling tools are used for studies such as load flow, fault level, dynamic stability and harmonics. Steady state analysis, such as load flow and fault level studies, is performed to assess the thermal loading,

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voltage profile and steady-state reactive capability of a network under pre-determined conditions. Dynamic analysis involves carrying out studies in the time domain to understand how networks and their components react to disturbances. This includes studies such as fault ride through, which seeks to understand generator recovery capabilities in the event of a fault. Harmonic analysis is undertaken, generally for a new connection to determine its contribution to the total harmonic distortion in the area, and if it exacerbates any resonant frequencies (Hay *et al*., 2015).

Load flow research represent an electrical energy grid examination considering the steady state computation in the presence of the inequality constraints that characterize the grid operation. Moreover, power flow solution inform about the active and reactive power flow, power losses and difference between the voltage values at various busbars. In accordance with (Kumar *et al.*, 2016) for the design process of a new power grid, the expansion planning of the aforementioned one in order to increase the demand is imperative. The decisions for power grid reinforcements, expansions and rehabilitation is usually based on the conclusions of load flow and stability analyses.

For achieving analysis of a power grid, the modeling process must include all power components, respectively: generating points, transformers from stations or substations, transmission and distribution lines and final consumers. A lot of attention can be payed to modelling of the aforementioned devices. Particularly, the loads modelling has received less attention and remains a syncope in the future development of the power grid. Meanwhile, latter researches have inform that the load modelling have a major influence on steady state results (Neagu *et al.*, 2014). Therefore, the improvement of load-models have a great importance. Power system simulations incorporate robust mathematical representations of real-life systems by using advanced modelling techniques to assess the interactions of individual component models (Afolabi *et al.*, 2015).

In this paper, a comparative study regarding the problem of power flow computation in HV distribution systems is performed. For this reason, in the following sections the theoretical aspects and a study case were presented. Thus, in section two are synthetically presented the four commercial power system simulation tools. Section three deals with the problem statement based on the Newton-Raphson method, and in the last section a case example is proposed. The simulation results are compared using parameters of computation time and the convergence rate. Finally, several conclusions are drawn.

2. Software Tools Used in Power Systems Simulation

The aforementioned commercial software packages used in the paper are synthetically described in the following.

A. *DIgSILENT PowerFactory* are a famous power system simulation tool, that combine all required functions, easy to use, and which integrate the stable and adaptable power network modelling capabilities with state-of-the-art methods and a unique database theory (digsilent.de).

B. *ETAP* is a full spectrum analytical engineering application tool, which analyse, simulate, monitor, control, optimize, and automate power grids (Aswani *et al.*, 2014). This simulation tool offers a comprehensive suite of integrated power grid result, which spans from the design to the operation process (etap.com).

C. *NEPLAN* Electricity is a software tool used to analyse, plan, optimize and simulate networks. The user-friendly graphical interface allows the user to perform study cases very efficiently. The customizable software has a modular concept and covers all electrical aspects in transmission, distribution, generation / industrial networks (neplan.ch).

D. *PowerWorld Simulator* is an interdependent power grid simulation tool created for power network steady-state operation with a duration between a few minutes to some days. This application tool have a highly effective load flow analysis capable of efficiently solving systems of up to 250,000 buses (powerworld.com).

The anterior presented software (*A*, *B*, *C* or *D*) is widely used in power systems analysis, and indeed globally, to perform these types of studies.

3. Problem Formulation. Newton Raphson Method

The steady state evaluation can be directly obtained following some repeated stationary state computation. For a power network with a known configuration, that includes all kind of buses (*PQ, PU* and slack), following the steady state computation, we obtain the nodal voltages and power flows on all network elements. The mathematical model leads to the solving of nonlinear algebraic equations, such as the following (Neagu *et al.*, 2012):

$$\begin{aligned} P_i &= G_{ii}U_i^2 + \sum_{\substack{k=1\\k\neq i}}^{n} U_iU_k\left[G_{ik}\cos\left(\delta_i-\delta_k\right)+B_{ik}\sin\left(\delta_i-\delta_k\right)\right];\\ Q_i &= -B_{ii}U_i^2 - \sum_{\substack{k=1\\k\neq i}}^{n} U_iU_k\left[B_{ik}\cos\left(\delta_i-\delta_k\right)-G_{ik}\sin\left(\delta_i-\delta_k\right)\right], \end{aligned} \tag{1}$$

where: P_i, Q_i is the active and reactive powers injected in the network node *i*; G_{ii}, G_{ik}, B_{ii}, B_{ik} – real and imaginary parts of the elements of the nodal admittance matrix corresponding to the analyzed network; U_i, U_k, δ_i, δ_k – modules and arguments of voltages in analyzed network nodes *i* and *k*.

Newton-Raphson algorithm is an iterative operation where many non-linear simultaneous equations is approximated into linear simultaneous equations using Taylor’s series expansion (Sharma *et al.*, 2010). In an N-busbar power network n equations for active power flow (P_i) and another n-equations for reactive power flow (Q_i) are presented. Then, is known that the number of unknowns is $2(n – 1)$ at the slack bus the voltage and must be maintain constant both in magnitude and phase. Following the permanent operating state computation using one of the mentioned methods, and one of specialized computation applications respectively, we obtain the power flows on the elements of the network, determined by relations such as (Georgescu *et al.*, 2012):

- for power lines:

$$\begin{aligned} \underline{S}_{ik} &= U_i^2 \underline{y}_{ik_0}^* + \underline{U}_{ki}\left(\underline{U}_i - \underline{U}_k\right)^* \underline{Y}_{ik}^* \\ \underline{S}_{ki} &= U_k^2 \underline{y}_{ki_0}^* + \underline{U}_k\left(\underline{U}_k - \underline{U}_i\right)^* \underline{Y}_{ik}^* \end{aligned} \tag{2}$$

- for transformers with real transformation ratio:

$$\begin{aligned} \underline{S}_{ik} &= \underline{U}_i\left(\underline{U}_k + N_{i'i}\underline{U}_i\right)^* \underline{Y}_{ik}^* \\ \underline{S}_{ki} &= \underline{U}_k\left(\underline{U}_i + \underline{U}_k / N_{i'i}\right)^* \underline{Y}_{ik}^* \end{aligned} \tag{3}$$

The active and reactive losses in a certain network element located between the *i* and *k* nodes are determined through the following relation:

$$\Delta\underline{S}_{ik} = \Delta P_{ik} + j\Delta Q_{ik} = \underline{S}_{ik} + \underline{S}_{ki} \tag{4}$$

By adopting some additional simplifying hypotheses (considering elements only through reactance, estimating the voltages in the nodes through their rated values and eliminating the trigonometric functions, taking into account that the phase differences of the voltages at the terminals of the elements are low), the equations (1) become linear, such as the following:

$$P_i = U_{n,i} \sum_{\substack{k=1 \\ k \neq i}}^{n} U_{n,k} B_{ik}\left(\delta_i - \delta_k\right); \quad i = \overline{1,n}; \; i \neq e\,, \tag{5}$$

where: $U_{n,i}$, $U_{n,k}$ is the nominal voltages of the *i* and *k* nodes.

By solving the equations system (5) in relation with the arguments of the nodal voltages, the active power flows on all network elements are determined, that is:

$$\begin{aligned} P_{ik} &= B_{ik} U_{n,i} U_{n,k}\left(\delta_i - \delta_k\right) \\ P_{ki} &= -P_{ki}; \qquad i = \overline{1,n}; \;\; i \neq k \end{aligned} \tag{6}$$

and active power losses on the entire power network shall be determined with the following expression:

$$\Delta P=\sum_{i=1}^{n-1}\sum_{k=i+1}^{n}\frac{P_{ik}^2}{U_{n,i}U_{n,k}}R_{ik} \tag{7}$$

The novel estimates for bus voltage are the following:

$$\begin{aligned}\delta^{(k+1)} &= \delta_i^{(k+1)}+\Delta\delta_i^{(k)}\\ \left|U^{(k+1)}\right| &= \left|U_i^{(k)}\right|+\Delta\left|U_i^{(k)}\right|\end{aligned} \tag{8}$$

Newton-Raphson is the most iterative method used for the load flow because its convergence characteristics are relatively more powerful compared to other alternative processes (Sereeter *et al.*, 2017), because their reliability is comparatively good since it can solve cases that lead to divergence with other popular processes. If the assumed value is near the solution, then the result is obtained very quickly, but if the assumed value is farther away from the solution then the method may take longer to converge (Afolabi *et al.*, 2015).

4. Case Study. Results and Discussion

Different simulation tools use different mathematical approaches to solve the load flow concept for a real network. In order to analyse the load flow, and a real HV electricity distribution network was considered. Then, for the proposed load flow studies, the following application packages were taken into account: DigSilent Power Factory, NEPLAN, ETAP and Power World Simulator. All of them are based on Newton-Raphson method, being the most known commercial application for power flow studies.

The single line diagrams from the four tools is presented in Fig. 1. Moreover, the computation error is 0.001. The network parameters (the resistance, the inductive reactance and the capacitive susceptance) results from the cross-sections (mm^2) and length (km) of each power lines. Table 1 details the busbar and branch system input data associated with the network. Input parameters for cables and overhead lines are given here in absolute values format. The network here is kept small in order to allow the first-time user to become rapidly familiar with the procedures for load flows.

The busbars are first set up in the program by name and number and in some cases by zone. Bus parameters are then entered according to type. A ‘slack bus’ is a busbar where the generation values, P (real power in MW) and Q (reactive power in MVAr), are unknown; there will always be one such busbar in any system. The active and reactive power injected in all network buses at peak load for a working day are indicated in Table 2. Our proposed network has 110 kV for nominal voltage, and the slack bus has for the peak load 118 kV. Taking into account the purpose of the paper to study and compare the load flow results of a distribution system at peak load, in Table 3 are indicated the voltage magnitude obtained with the four specialized tools (with one iteration and 0.02 seconds as computational time).

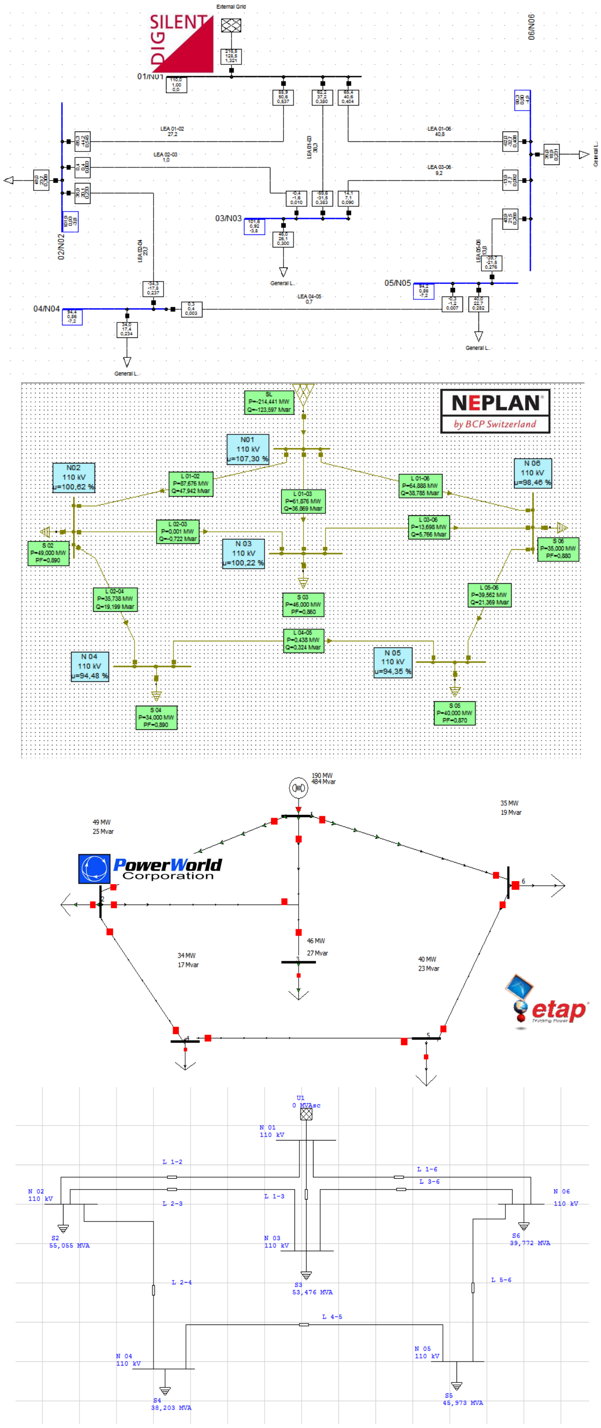

Fig. 1 − The HV test distribution network from the four application tools.

Table 1

The Specific and Global Parameters of the Cable from the HV Distribution Network

No. of lines	Bus *i*	Bus *j*	Length (km)	Sections [mm^2]	r_0 [Ω/km]	x_0 [Ω/km]	b_0 [μS/km]	*R* [Ω]	*X* [Ω]	*B* [μS]
1	1	2	50	2x185	0.161	0.430	2.66	4.03	10.75	266.00
2	1	3	36	185	0.161	0.430	2.66	5.80	15.48	95.76
3	1	6	43	185	0.161	0.430	2.66	6.92	18.49	114.38
4	2	3	47	150	0.198	0.440	2.59	9.31	20.68	121.73
5	2	4	48	150	0.198	0.440	2.59	9.50	21.12	124.32
6	3	6	39	150	0.198	0.440	2.59	7.72	17.16	101.01
7	4	5	35	150	0.198	0.440	2.59	6.93	15.40	90.65
8	5	6	56	2x150	0.198	0.440	2.59	5.54	12.32	290.08

Table 2

Active and Reactive Power Injected in the HV Distribution Network Buses

No. of bus	*P* [MW]	*Q* [MVar]
2	39	25.1
3	46	27.3
4	34	17.4
5	40	22.7
6	35	18.9

Table 3

The Absolute Values of Voltage (kV) from Power Flow Results

No. of bus	DigSilent	NEPLAN	ETAP	Power World
1	118.000	118.000	118.000	118.000
2	110.687	110.684	110.681	110.686
3	110.454	110.247	110.312	110.454
4	103.973	103.932	103.951	103.972
5	103.847	103.782	103.637	103.847
6	108.390	108.308	108.352	108.390

It can be observed in Table 3 that the voltage magnitudes at all the buses (except the slack bus) are around 110 kV. The lowest voltage was observed on bus 4 and bus 5 for all used tools. By using the load flow functions based on the Newton-Raphson method, the active power losses result for the proposed HV distribution network are shown in Table 4.

The total active losses are drawn in Fig. 2. The voltage form bus 4 and 5 in are illustrated in Fig. 3. From the last two figures we can observe the smallest difference between the results of the four used application, compared with the

Romanian voltage regulation limits, *i.e* for our proposed HV electricity network the minimum value is –5% or 104.5 kV), (Georgescu *et al*., 2012).

Table 4
The Active Power Losses (MW) on the Power Lines

No. of lines	Bus i	Bus j	DigSilent	NEPLAN	ETAP	Power World
1	1	2	3.002	2.937	2.928	2.942
2	1	3	2.216	2.179	2.139	2.114
3	1	6	2.932	2.871	2.893	2.838
4	2	3	0.001	0.001	0.001	0.001
5	2	4	1.263	1.299	1.300	1.288
6	3	6	0.182	0.145	0.160	0.155
7	4	5	0.001	0.001	0.001	0.001
8	5	6	1.022	1.008	1.012	1.013

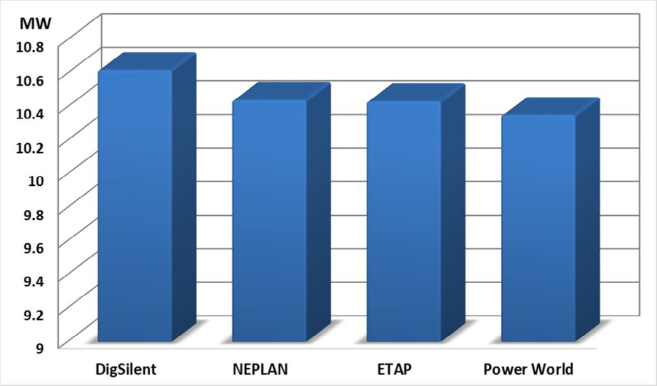

Fig. 2 – The total active power losses for the HV distribution network.

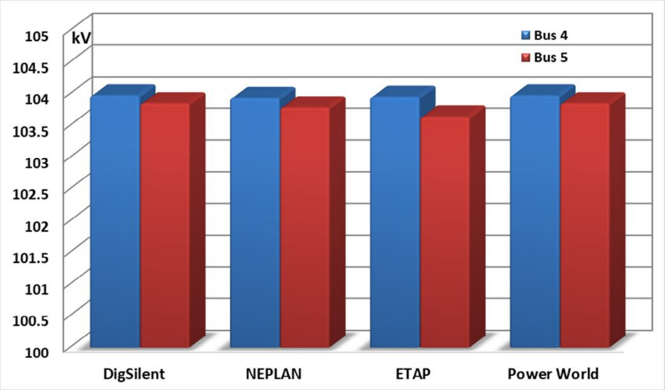

Fig. 3 – The voltage magnitude results for bus 4 and bus 5.

The Newton–Raphson algorithm is a powerful method for solving a set of non-linear equations, the advantages of them are that it is not sensitive to the assumption of the solution vector made. The solution converges in most cases as compared to the Gauss-Seidel method and it is done in a fewer number of iterations. The drawback of this method is increased computational burden and the need of additional storage space since it involves calculation of Jacobian matrices and storage of values of previous iterations. At any iteration, the function is approximated by a tangent hyperplane and the problem is linearized into a Jacobian-matrix equation (Afolabi *et al*., 2015). Regarding the results, the 6-bus distribution network was proposed only from the simplicity point of view, because in all studied commercial application the same method for power flow computation was used. If the bus numbers increase, the simulations parameters will change accordingly. For our purpose, the HV real network are relevant. The one iteration number resulted the same for all four analysed tools, but the computation time results vary between 0.0201 (Digsilent) to 00219 (ETAP).

5. Conclusions

In this research, the steady state simulation based on power flow analysis of a HV distribution network was carried out. The research in this paper summarises the use of computer-based software for simulation and analysis of power systems. It is obvious from the graphs that for peak load the iteration is effectively run in convergence of Newton-Raphson method for each considered software studied. Not only the power losses are under controlled but also voltage values are sensitively close to each other. The main conclusion is that for a simple load flow computation we can use any tool from the aforementioned, with small computation errors both for load flow and voltage magnitude.

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ANALIZA COMPARATIVĂ A REGIMULUI PERMANENT DE FUNCȚIONARE UTILIZÂND APLICAȚII COMERCIALE DE SIMULARE A REȚELELOR ELECTRICE

(Rezumat)

Lucrarea propune o analiză comparativă a calculului regimului permanent de funcționare pentru rețelele de distribuție de înaltă tensiune (HV). Studiul regimului permanent are o importanță deosebită în planificarea dezvoltării rețelelor electrice, pentru determinarea celor mai bune condiții de funcționare. În acest scop, au fost testate patru din cele mai utilizate programe comperciale de analiză a rețelelor electrice. În primul rând, s-a vizat calculul circulațiilor de putere activă şi reactivă şi pierderile de putere activă, iar în al doilea rând, tensiunile nodale şi încărcările liniilor. Ambele probleme au fost rezolvate folosind metoda Newton Raphson. Dispunând de informații reale de sarcină, furnizate de sistemele SCADA, obiectivul lucrării coincide cu testarea fiecărui instrument în vederea obținerii de rezultate de regim permanent. Pentru a compara rezultatele, a fost utilizată o rețea reală de distribuție de înaltă tensiune. Rezultatele tuturor instrumentelor propuse au fost comparate şi au fost trase concluzii.