

AN EXAMPLE OF USING MICROSOFT EXCEL SOLVER FOR POWER NETWORK CALCULATIONS

Čedomir ZELJKOVIĆ¹, Mićo GAČANOVIĆ²

Abstract: Power-flow problems in electrical power networks have been investigated over the years and several calculation methods were introduced. In order to determine the work state of a power network, it is often necessary to solve a large system of non-linear transcendent equations. Therefore, the program routines are complex to develop, while specialized commercial software packages are expensive and not easily available.

On the other hand, Microsoft Excel as a part of Microsoft Office software package is widely-spread in the world and relatively easily available. Excel possesses a plug-in named Solver which is a powerful tool for constrained optimization and solving of non-linear equations. Solver can be used in power network calculations for both practical and educational purposes. Solver is also applicable to the other problems concerning electrical theory and practice (circuit theory, electromagnetics, etc.).

Keywords: Electrical Power System, Power Flow, Computational Methods, Microsoft Excel Solver.

INTRODUCTION

In power flow analysis, it is expected to determine steady-state powers and voltages of the transmission system. The calculation is analogous to the familiar problem of solving for the steady-state voltages and currents in a circuit and is just fundamental. It is an integral part of most studies in system planning and operation and is, in fact, the most common of power system computer calculations [1].

Power flow problem exists for a long time and there are a lot of algorithms introduced for its solving. There are also a lot of specialized software programs which are commercial and mostly expensive.

This paper describes how one of the most widely-spread software packages for spreadsheet calculations, Microsoft Excel, can be used for solving the power flow problems. Excel contains integrated plug-in called Solver, with optimization and equation solving as the basic purposes, which can be adjusted for power flow calculations.

Solver is also applicable to the other problems concerning electrical theory and practice (circuit theory, electromagnetics, etc.), so it deserves a more detailed study.

THE POWER FLOW PROBLEM

In this analysis the transmission system is modeled by a set of buses (nodes) interconnected by transmission links. Generators and loads, connected to various nodes of the system, inject and remove power from the transmission system.

The power flow problem is given by the following two sets of non-linear equations:

$$p_i = \sum_{j=1}^N u_i u_j [g_{ij} \cos(\theta_i - \theta_j) + b_{ij} \sin(\theta_i - \theta_j)] \quad (1)$$

$$q_i = \sum_{j=1}^N u_i u_j [g_{ij} \sin(\theta_i - \theta_j) - b_{ij} \cos(\theta_i - \theta_j)] \quad (2)$$

where

- p, q active and reactive power injections
- u, θ bus voltage quantifiers – magnitude and angle
- g, b conductance and susceptance, members of network admittance matrix.

If the network configuration is not variable, the correspondent network admittance matrix has constant elements and the only variables in the power flow equations are power injections, voltage magnitudes and angles. But it should be noticed that there are $4N$ variables in $2N$ equations if N is the number of the network nodes. Therefore, unique solution can only be reached by prespecifying $2N$ values for variables. Another way is searching for the group of solutions and accepting the optimal one in respect to some determined criteria.

In both solution ways there exists the same problem because the state variables cannot be explicitly expressed and their values must be found by an iterative process. Historically, some classic iterative procedures have been used such as Newton-Raphson, Gauss-Seidel or Stott-Alsac decoupled iterative schemes. But Solver is able to replace any of them, furthermore, it is able to find optimal solution in respect to one or more criteria. Solver can also comprise enforced equality or inequality constraints.

SOLVER

Solver background

Microsoft Excel was able to solve equations from its early versions. Feature *Goal Seek* enables finding roots of single equations. By an iterative procedure numerical value in the independent cell is varied in order to get desired value in formula dependent target cell. At the end of the process, independent cell contains equation solution. *Goal Seek* is quick and simple to use, but it can only be used for univariate problems. However, several last versions of Excel are distributed with a more powerful tool – *Solver*, which is capable of solving much more complex

¹ University of Banja Luka, Department of Power Engineering, Patre 5, 78000 Banja Luka, Bosnia&Herzegovina, E-mail: cedimir@etfbl.net

² University of Banja Luka, Department of Power Engineering, Patre 5, 78000 Banja Luka, Bosnia&Herzegovina, E-mail: bilchy@blic.net

problems. Solver deals with up to 200 variables and allows up to 200 constraints.

For the linear problems, Solver uses the *simplex* method. What is more important here, Solver is also capable of handling non-linear problems by employing a *generalized reduced gradient method*. In cases where the problem being solved requires integer-valued variables, Solver also employs a *branch and bound* algorithm.

Configuring Solver

The user can partially participate in the control of Solver's iterative algorithm by filling the edit boxes in *Solver Options* dialog. Figure 1 presents this dialog.

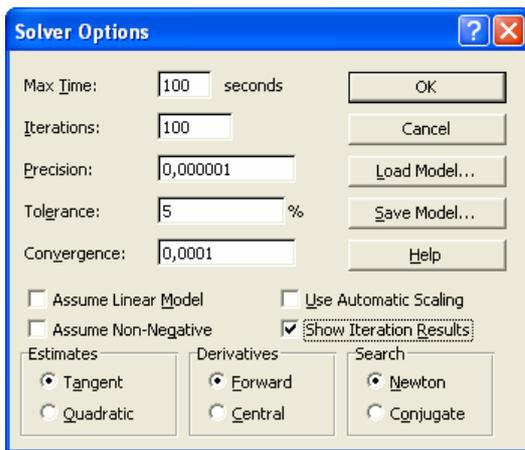


Fig.1 – Configuration dialog

Max Time represents the maximum amount of time to allow Solver to obtain a solution, after which the process will be aborted. Solver will display a message box saying that it could not find a solution within the allowable time.

Iterations specifies the maximum number of iterations to allow Solver while attempting to find a solution. If the maximum number of iterations is reached before Solver finds a solution, the process will be aborted and Solver will display a message box saying that it could not find a solution within the allowable number of iterations.

Precision is specified as a decimal number between 0 and 1, with a default value of 1.0×10^{-6} . It is used by Solver to determine when a constraint is satisfied. The lower the value specified here, the higher the precision.

Tolerance is used to determine whether or not an integer-valued constraint is satisfied. Tolerance is expressed as a percentage, with a default value of 5%. If integer constraints are not used, then Tolerance does not apply.

Convergence is used to determine whether or not Solver has converged on a solution. Solver considers a solution converged upon when the optimal values are within the value specified in the Convergence field over the last five solution iterations. Solver will display a message box after it converges on a solution. Solver will continue trying to converge so long as the specified maximum number of iterations or maximum time has not been reached. If either limit is reached, Solver will display a message box indicating that it could not converge.

In cases when the problem model is linear or there are expected non-negative results user can check *Assume Linear Model* or *Assume Non-Negative*.

Use Automatic Scaling is the option which can be used in solving some problems where the values of the independent variables and dependent variables may differ widely in magnitude. In these cases it's prudent to scale the model so that the magnitudes of the input and output values are of the same order. If the model has not been already set up with scaling, this option will allow Solver to perform the scaling instead of the user.

If needed to follow the Solver's progress as it iterates when solving a problem, it is possible to check the *Show Iteration Results* option. Then a dialog box will appear, saying that Solver is paused and that the current iteration's results are displayed on the active worksheet. [3]

SOLVER APPLICATION TO A TEST SYSTEM

Example Test System

The system used to test the solution algorithm is the 4-bus three-phase transmission network. Constant parameters and specified values expressed in per unit are given with the network elements. Transformers are assumed to have been absorbed into the generator, load or transmission line models and are not shown explicitly.

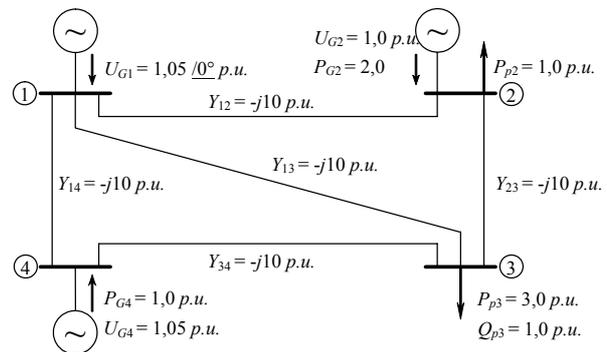


Fig.2 – One-line diagram of the test system [5]

Solution of the basic power-flow problem

Power flow equations (1) and (2) are simultaneous and non-linear, therefore it is not possible to find the problem solution explicitly. Microsoft Excel Solver is a suitable tool that can help; it is enough to adapt the initial problem to the form of an optimization task.

It can be noticed (figure 3), that in the Solver iterative process it is not needed to use Jacobian or *B*-matrices, which are necessary during Newton-Raphson or Stott-Alsac procedures. It is enough to enter power flow equations – formulas for power injections versus angles and magnitudes of bus voltages. It is also necessary to form active and reactive power mismatch vectors, that contain temporary differences between prespecified and computed power injections:

$$\Delta p_i = p_i^{spec} - p_i \quad (3)$$

$$\Delta q_i = q_i^{spec} - q_i \quad (4)$$

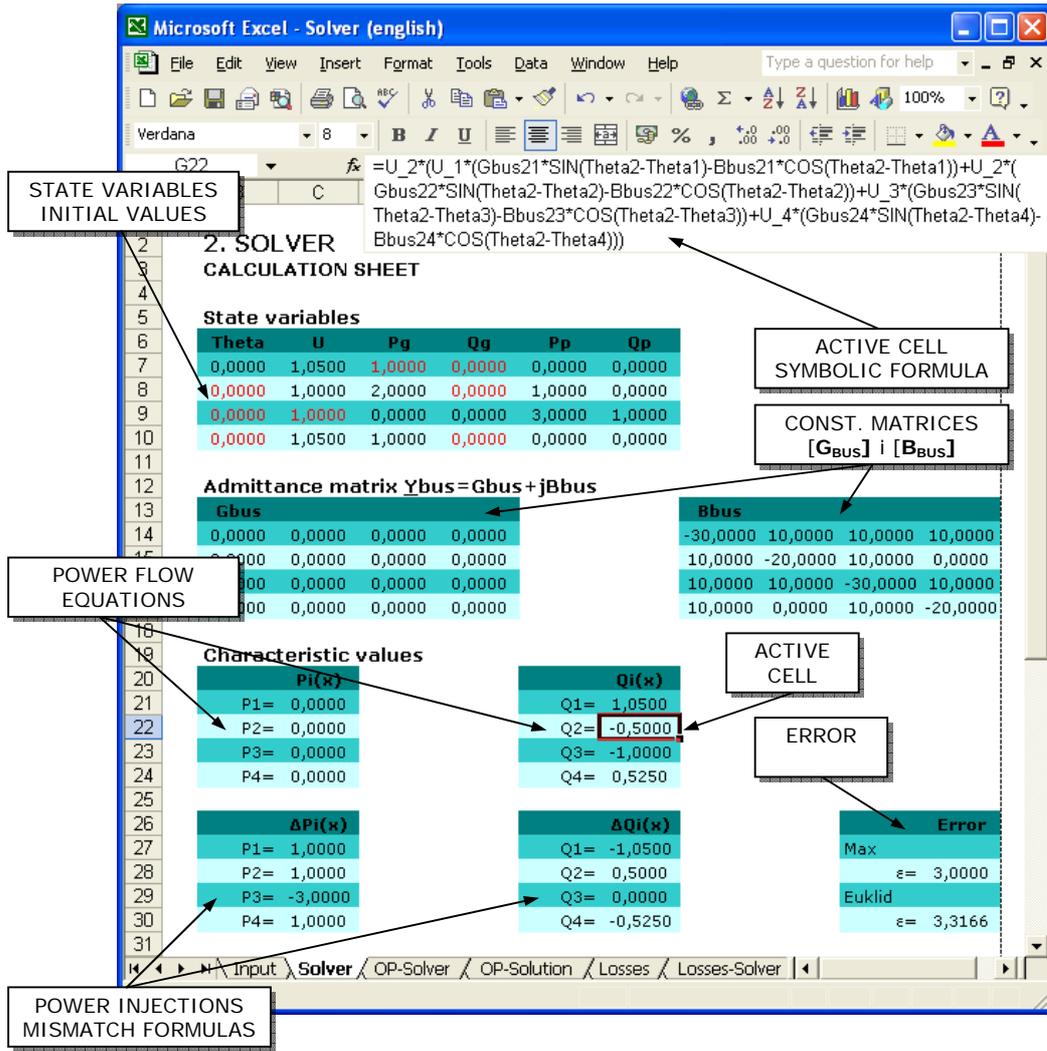


Fig.3 – The basic Excel sheet with solver calculation before the start of the procedure

Entering formula for temporary error is essential for this computational method. Temporary error is the module of the mismatch vector and the main point is to minimize this value.

$$error = \|\Delta x^k\| = \max_j |\Delta x_j|, \quad j = \overline{1,2i} \quad (5)$$

where Δx^k is the mismatch vector that contains all Δp_i and Δq_i elements. Also, Euclid definition for the vector module can be used:

$$\|\Delta x^k\| = \sqrt{\sum_i \Delta x_i^2}, \quad j = \overline{1,2i} \quad (6)$$

With the calculation platform prepared, it is possible to get down to solving the basic problem. First step is the choice of initial values for the state variables. *Flat start* is chosen, which means that all voltage angles are set to 0 and all voltage magnitudes to 1.000 [p.u.], although the procedure can also successfully start with different initialization. After that, dialog *Solver Parameters* is filled (figure 4). Here, the cell \$K\$28 which contains error formula is chosen for the target cell. It is requested that the target cell has to be equal to zero, naturally, at the level of adjusted accuracy. By filling the box *By Changing Cells*

calculation variables are chosen. The expression \$B\$8:\$B\$10;\$C\$9;\$D\$7;\$E\$7:\$E\$8;\$E\$10 tells that chosen variables are angles from θ_2 to θ_4 , voltage magnitude u_3 , active output of the slack generator p_1 , and reactive outputs q_1 , q_2 and q_4 , all initially unknown. The other values are assumed to be constant.

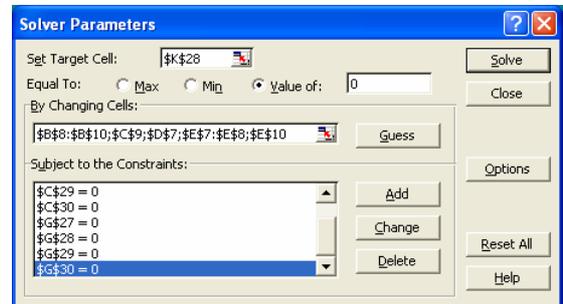


Fig.4 – Filling the Solver Parameters dialog

The basic problem has no constraints enforced, but it can be shown that the procedure convergence will be faster if the zero power mismatches are defined as equality constraints. By clicking the button *Add*, a new dialog *Add Constraint* is opened for editing.

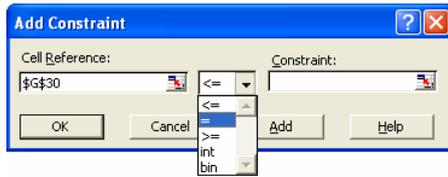


Fig.5 – Defining the constraints of the problem

The next step is configuring the iterative process by using the dialog *Solver Options*, where one of the suitable configuration is shown in figure 1.

At the end, the button *Solve* is pressed and after 7 iterations (with this configuration), message of successful solution is achieved. The error and the power injections mismatches are annihilated, while variable cells contain acceptable values as a solution of the problem.

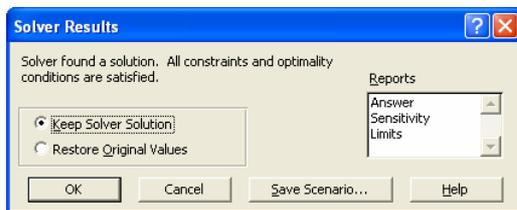


Fig.6 – Final Solver message

Table I

Solution of the basic problem

Bus	$\Theta_i [^\circ]$	$U_i [\text{p.u.}]$	$P_g [\text{p.u.}]$	$Q_g [\text{p.u.}]$	$P_p [\text{p.u.}]$	$Q_p [\text{p.u.}]$
1	0.0000	1.0500	1.0000	1.1524	0.0000	0.0000
2	0.1010	1.0000	2.0000	-0.4008	1.0000	0.0000
3	-5.5603	0.9949	0.0000	0.0000	3.0000	1.0000
4	-0.0327	1.0500	1.0000	0.6268	0.0000	0.0000

Treatment of Active Losses

The basic problem is simplified and the losses of active power were not treated. Reactive part of the line impedance is not a good model for losses computation, therefore the line resistance is also to be taken into consideration. Initial value of line impedance $\underline{Y}_L = -j10$ [p.u.] will here be replaced with milder approximation $\underline{Y}_L = 1-j10$ [p.u.].

Following the computation instructions defined earlier, the new results are reached (Table II).

Table II

Network variables with active losses included

Bus	$\Theta_i [^\circ]$	$U_i [\text{p.u.}]$	$P_g [\text{p.u.}]$	$Q_g [\text{p.u.}]$	$P_p [\text{p.u.}]$	$Q_p [\text{p.u.}]$
1	0.0000	1.0500	1.0382	1.1587	0.0000	0.0000
2	0.3322	1.0000	2.0000	-0.4071	1.0000	0.0000
3	-5.3153	0.9852	0.0000	0.0000	3.0000	1.0000
4	-0.0823	1.0500	1.0000	0.6307	0.0000	0.0000

It can be noticed that slack generator in this example produces the amount of 1.0382 [p.u.] of real power which can be compared to 1.000 [p.u.] in a simplified problem. The difference of 0.0382 [p.u.] exactly presents the active power losses for the whole network. As expected, the consumer bus voltage (bus 3) is reduced. Of course, bus voltage angles are also slightly changed.

Transaction Problems

Power transaction is one of the characteristics of de-regulated power systems. Solver can help in analysis of effects when one power plant has to take some tasks of another one. In this example, it is assumed that generator G4 has to take on the production of 1.000 [p.u.] active power of generator G2, so that consumers are properly supplied without interruptions. After the change of input data and the new Solver iterative procedure, actual state of the power network can be determined.

Table III

Consequences of the transaction

Bus	$\Theta_i [^\circ]$	$U_i [\text{p.u.}]$	$P_g [\text{p.u.}]$	$Q_g [\text{p.u.}]$	$P_p [\text{p.u.}]$	$Q_p [\text{p.u.}]$
1	0.0000	1.0500	1.0466	1.1867	0.0000	0.0000
2	-2.4876	1.0000	1.0000	-0.3262	1.0000	0.0000
3	-5.3291	0.9845	0.0000	0.0000	3.0000	1.0000
4	2.5842	1.0500	2.0000	0.6054	0.0000	0.0000

The first conclusion is that the state of the network got worse. The consumer bus voltage is insignificantly lowered, but key negative product is increase of total active power losses (0.0466 [p.u.] compared to 0.0382 [p.u.], which presents about 22%). Slack generator has to compensate for these losses.

Optimal Power Flow Problem (OPF)

Optimal power flow computation is one of the most complicated problems in power systems analysis. However, Solver is able to deal with such problems as well which is one reason more to make a positive decision about the strength of this software tool.

Solution of the OPF problem is a state of the power network in accordance with some imposed criteria. This paper presented the example of minimization of active losses, but also the other optimization criteria can be respected. Therefore, the initial active power output is not prespecified for any of generators because they also present variables now. The cell with the formula for total power losses (P_γ) is now declared as the target cell and the option for its minimization is selected here. At the end of Solver's iterative procedure total active power losses amount to 0.03817 [p.u.].

Table IV

Network variables during the optimal power flow

Bus	$\Theta_i [^\circ]$	$U_i [\text{p.u.}]$	$P_g [\text{p.u.}]$	$Q_g [\text{p.u.}]$	$P_p [\text{p.u.}]$	$Q_p [\text{p.u.}]$
1	0.0000	1.0500	1.0976	1.1539	0.0000	0.0000
2	0.0000	1.0000	1.8954	-0.4011	1.0000	0.0000
3	-5.3945	0.9852	0.0000	0.0000	3.0000	1.0000
4	0.0000	1.0500	1.0451	0.6289	0.0000	0.0000

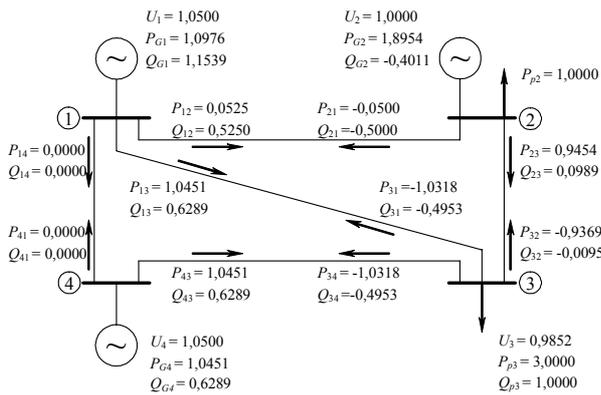


Fig.7 – Power flow solution with active power losses minimized

Area for Further Modifications and Development

Potential user could use number crunching platform constructed in this way in order to investigate other facts and phenomena concerning power flow analysis. It is possible to vary the quantities which were constant in previous calculations or to introduce new aspects and change the goals of analysis.

Some of the possible variants are:

- Alteration of line admittances – length variations;
- Change of R/X (G/B) ratio – introduction of different types of transmission lines;
- Testing of Voltage/Reactive occasions by varying pre-specified generator voltages;
- Testing the costumer impact on power flows;
- Power flow optimization by applying other criteria;
- Testing other transactions;...

CONCLUSION

This paper shows that the significance of the spreadsheet programs in power systems analysis and the other electrical disciplines cannot be neglected. Microsoft Excel as the most distributed spreadsheet software package calls for attention because of its strength and relatively easy use. It is suitable for both practical and educational purposes thanks to great number of implemented functions, especially mathematical and statistical. By means of this program it is possible to solve electrical problems and analyze different events and phenomena as well as to show parallel calculation results. Software extensions (*Add-Ins*) bring additional power and open new areas of application.

Microsoft Excel is in the golden mean when talking about electrical applications. Software based on code typing (Matlab, C++, Fortran,...) has more possibilities but also requires greater knowledge and preparation, and therefore has much less admirers. On the other hand, software packages specialized for electrical calculations offer the easiest way toward problem solution but their rela-

tively high market price makes this option not so easily available.

This article showed, by presenting one simple example, just a small bit of Excel Solver's potential. But it's noticed that it makes sense to invest in knowledge broadening concerning Microsoft Excel powerful features.

REFERENCES

- [1] A. R. Bergen, V. Vittal: "Power systems analysis", Prentice Hall, 2000, New Jersey.
- [2] D. Fylstra, L. Lasdon, J. Watson, A. Waren: "Design and use of the Microsoft Excel Solver", Interfaces, Vol. 28, No. 5, 1998, pp. 29-55.
- [3] D. M. Bourg: "Excel scientific and engineering cookbook", O'Reilly, 2006, Sebastopol.
- [4] Microsoft article 82890: "Solver uses generalized reduced gradient algorithm", 2005.
- [5] N. Rajaković, M. Čalović, P. Stefanov, A. Savić: "100 rešenih zadataka iz analize elektroenergetskih sistema", Akademska misao, 2002, Beograd.
- [6] A. Dimitrovski, K. Tomsovic: "Boundary load flow solutions", IEEE Transactions on Power Systems, Vol. 19, No. 1, 2004, pp. 348-355.



Čedomir Zeljković was born in 1978. He received the Dipl. Ing. degree in Electric Power Engineering from the Faculty of Electrical Engineering, University of Banja Luka in 2003. Since 2004, he is a graduate student at the Faculty of Electrical Engineering, University of Belgrade, working towards his M.Sc. degree. He works as engineer for high voltage and low voltage switchgears at the Hydropower plant "Bočac". He is also a part-time research assistant at the Faculty of Electrical Engineering, University of Banja Luka. His areas of scientific interest are distributed generation and renewable sources in a power system, as well as power network calculations and optimization.



Dr. Mičo Gačanović was born in 1952. He is recognized and known internationally as a scientist in the field of applied electrostatics, where he has given his contribution through original solutions, which are patented in 136 countries throughout the world and applied in production. He received many prestigious world-known awards and certificates for his creative work. Hence, he is included in the work of world groups of creativity, research and new technology in Brussels, Moscow, Pittsburgh and other world cities. He is also involved in research projects from the field of theoretical electrical engineering in Germany, Belgium and Russia.

