COST Action TU1304 WINERCOST

Wind Energy Technology Reconsideration to Enhance the Concept of Smart Cities

Integration of wind power into power distribution grid
(STSM: TU1304 -35330)

STSM Scientific Report

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Introduction

The purpose of this Short Term Scientific Mission (STSM) was obtaining knowledge about efficient integration of small-scale wind power generation within power distribution grid.
As the visiting researcher, I've been especially interested in approaches and methods used by Host institution in various wind power integration studies.

The Host Institution, Electricity Coordinating Center Ltd. (EKC), Belgrade, has great experience from wind power integration studies completed worldwide. Increasing demand for wind power integration in both transmission and distribution grid recently, has resulted in increased involvement of EKC in meaning of expert analyze. Especially, initiatives for transformation of power distribution grids toward Smart Grid Concept, have resulted in increased engagement of EKC in distributed generation integration studies. These issues are in close relation with ones I am interested in COST Action TU 1304 " Wind Energy Technology Reconsideration to Enhance the Concept of Smart Cities".

At the beginning of this STSM, the work carried out in the STSM could be treated as the theory introduction with the latest EKC research in wind power integration. Although, a consideration of wind power integration into either transmission or distribution grid has many resemblances, there are details and particularities what cause in different analyze approaches. Since, small-scale wind power is distributed generation, so grid integration consideration is different from large-scale integration into transmission grid.
EKC uses the software PSS/E, the powerful tool for power grid computations and simulations. The software is designed as professional tool for modeling and analysis of a high voltage power transmission network, predominately. But, the latest versions offer many tools that medium and low voltage power distribution network can be simulated evenly. So, this software can be used as proper tool for simulation of distributed generation integration into distribution grid, i.e. into Smart Grid concept.

The practical example of grid integration analysis was used to introduce me with the technical requirements and constraints have to be fulfilled when connect small-sale wind turbines into power distribution grid. The requirements aren't as extensive as for the large-scale wind turbines but a responsible Distribution System Operator (DSO) imposes some, anyway. The analyzed case study is grid integration of two wind turbines, WT1 installed power of 1 MW, hub height 70 m and blades diameter of 54 m and WT2 installed power of 0.6 MW, hub height 55 m and blades diameter of 44 m. The wind turbines have to be connected to 20 kV distribution grid.

Background

Grid integration of wind turbines is being become complex task, in recent years. Intermittent and unpredictable production from renewable sources imposes new challenges to Transmission System Operators (TSOs) to keep power system in stable operation mode. Strong participation of wind power in a power system has jeopardized the power production/consumption balance. i.e. power system stability. Wind power fluctuations affect directly on a wind power production and consequently on a power transmission system stability. Unlike conventional sources, power production from wind generation can not be predicted precisely either in short or long term. So, the TSOs need as best as possible wind forecast and look for utmost weather intelligence in order to decrease unexpected wind power production drops and outages.

In some European countries, with high level of wind power penetration, installation of MW in wind power requires same amount of power reserves in conventional sources. This increases investment costs of wind power utilization projects significantly but provides TSOs with necessary power reserves necessary for reliable both power system operation and consumers power supply. It is obvious, when planning installation of large-scale wind turbines/farm, an importance to pay a special attention on each detail in grid integration calculations and simulations. It holds for both stability calculations, in stationary and dynamic state.

Small-scale wind turbines are connected to distribution power grid, either medium voltage (MV) or low voltage (LV) level.
Unlike large-scale wind turbines/farms, small-scale wind turbines have no such impact on a power system stability, but rather on local distribution grid power quality, likely. An interruption/sudden change in power production from small-scale wind turbine can affect on voltage quality, flickers and harmonics. If a distribution grid is not strong enough, like in rural regions, these phenomena could spoil power quality supply of end users.
Harmless influence on a power system stability is the one of the reasons why stability of a small-scale wind turbines isn't being scrutinized as for large-scale units. Furthermore, stability improvements in small-scale wind turbines, like capacitor banks and power electronics, shouldn't be cost effective comparing wind turbine size. When applying for a power grid connection, a distribution system operator requires that a wind generator produces power in allowed range of output voltage, total harmonics distortion (THD), flickers, usually.

Rapid development of renewable generation technology, followed by proper regulatory subsidy policies and electricity price increase, have motivated households to invest in small scale renewable generation unit, predominantly solar and wind power. This trend influences on transmission and distribution grid, so a supplied region is not passive any more but active.
Generally, variable production from the renewable sources, either small scale distributed or large scale, requires additional efforts from power system operators to keep power system in stable operational point. Regardless, distributed generations have some advantages against large scale production units:
- failure in one small-scale production units has less impact on grid stability, significantly,
- higher electricity supply independence,
- reduced transmission/distribution losses, electricity produced at local level is consumed in local,
- reduced investment capital risk (no huge investments in large-scale units),
- minor demands from TSO/DSO when integrating into power system,
- energy management on local/regional level – everyone will be able control your consumption/production, etc.

Well developed distribution network gives opportunity for distributed, not concentrated deployment of renewable sources within urban regions/cities. Distributed renewable generation is supposed to be main energy sources within smart cities/regions.

Description of the work carried out and main results obtained

Before introduction with the case study, EKC was engaged to analyze, I was introduced with the prevailing issues and obstacles in general, when scrutinize integration of small-scale wind turbines into power distribution grid.

- SOFTWARE TOOLS

Simulations and calculations are performed in software package PSS/E. It is professional software tool for simulation of large high voltage transmission networks predominantly, but MV and LV distributions networks can be simulated as well.
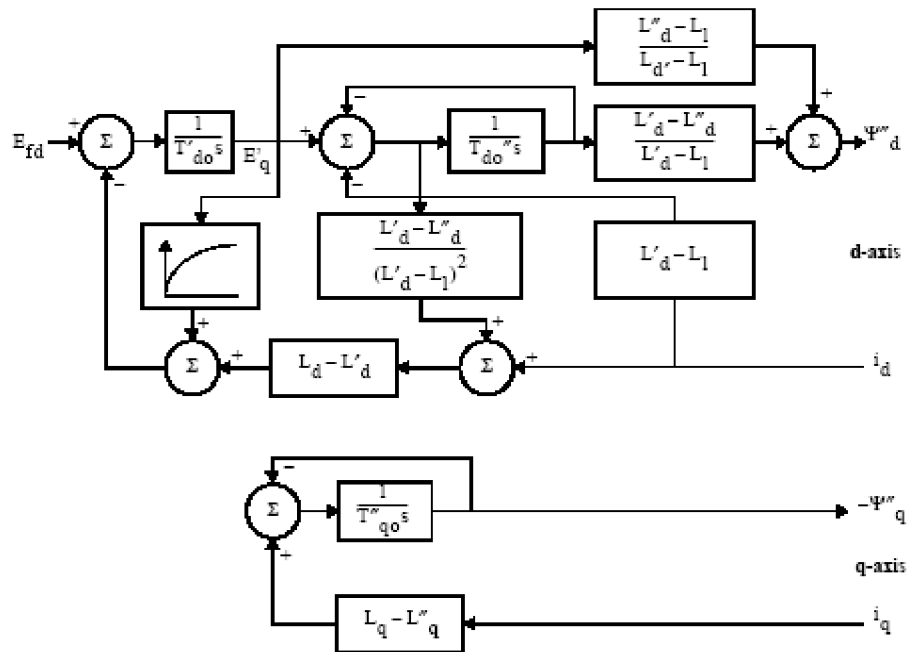

Figure 1: GENSAL - Salient pole generator model

I've been introduced with advanced new version of this software package and power generation/transmission/distribution element models, used in simulation. Vast of models can be found in the PSS/E Model Library, both for stationary and dynamic calculations, making work with this software very "User friendly". One of these models are presented in Figure 1, generator model GENSAL.

This software uses advanced user graphical interface with possibility of connecting implemented tools necessary for various calculations and simulations. Also, it is possible to create advanced textual and graphical reports based on calculation results. Figure 2 presents typical graphical environment of PSS/E software.

Figure 2: Graphical PSS/E software environment

Once a model completed, gives you opportunity for creation of reports, either textual or graphical, and for desired part of network (selected elements, selected region, designated distribution area, desired voltage transmission/distribution voltage level etc.). The steady state power flow of small-scale wind turbines connected to distribution network is presented in Figure 3.

The power flow calculations and voltage profiles are obtained by *Newton-Raphson* iterative procedure.

Figure 3: Power flow results in the one phase graphical report

- GRID INTEGRATION CALCULATIONS

After introductory lessons, the one case study, already completed by EKC, was working example for detailed examination of technical DSO requirements for small-scale wind turbine grid integration.
The case was integration of two wind turbines, WT1 1.0 MW and WT2 0.6 MW installed power, the generators are synchronous machines with salient pole (Figure 1 shows PSS/E model). The interface between grid and turbine is AC/DC/AC convertor, enabling stable production wind generator in various operating circumstances. The connection of the AC/DC/AC convertor with a wind turbine and power grid is presented in Figure 4. The cut in wind speed is 3-5 m/s, cut out 25 m/s and nominal wind speed is 12-13 m/s.
The generator voltage is 0.4 kV, connected to 20 kV distribution network by 20/04 kV wind turbine transformer. The produced power is either consumed by local consumption, simulated on 20 kV side, or evacuated by 20 kV distribution line to transmission grid by 110/x kV power substation (Figure 3). The WT1 and WT2 are connected to 110/20 kV power substation by 20 kV overhead transmission line at distance 2.0 km and 1.4 km, respectively. This solution increases investment costs, but increases reliability, since the wind turbines are independent on each other, i.e. each wind turbine has its connecting 20 kV line.
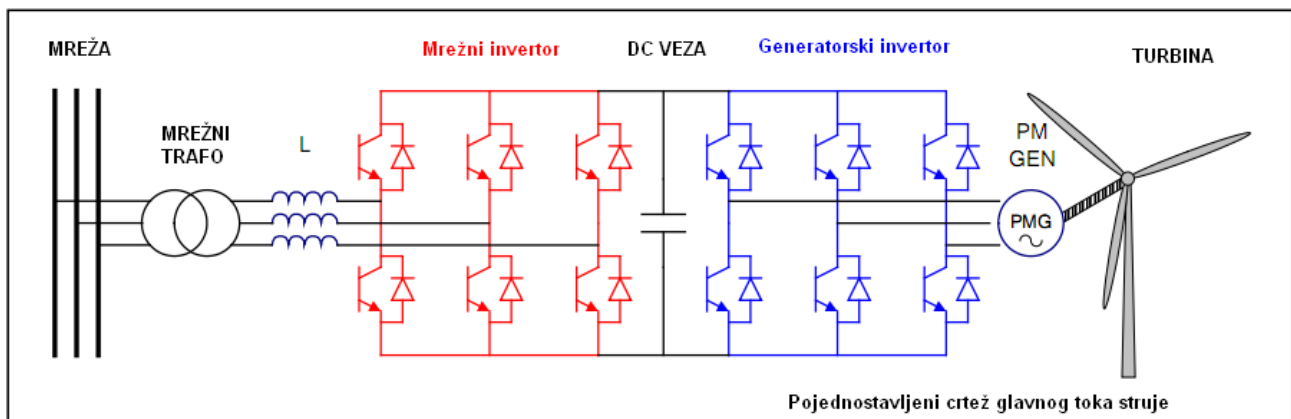

Figure 4: The principal layout of wind generator, AC/DC/AC convertor and 20/0.4 kV wind turbine transformer

The simulation model is created in PSS/E software tool and power flow calculations in steady state are presented in Figure 3. The *Newton-Raphson* iterative method converged and power flow steady state is achieved with all voltages and currents in allowed limits.

The power substation TS 110/20 kV Gacko has 110/20 kV, 20 MVA transformer with the nominal transformer ratio 115/20 kV with ±10% regulation range. The voltage-reactive power production analysis was performed, i.e. the influence of generator voltage variations (in range 0.9 -1.1. p.u.) on reactive power production and on 110 kV voltage was recorded. The three tap positions of 110/20 kV transformer are analyzed, i.e. 115/20 kV/kV, 120.75/20 kV/kV and 126.5/20 kV/kV. The wind turbines block-transformers 20/0.4 kV are set on nominal ratio. The results of analyses are presented in Figure 5 and Figure 6, i.e. rective power production in function of generator voltage - Qg = f(Ug) and 110 kV voltage dependance on generator voltage - U110 kV = f(Ug).

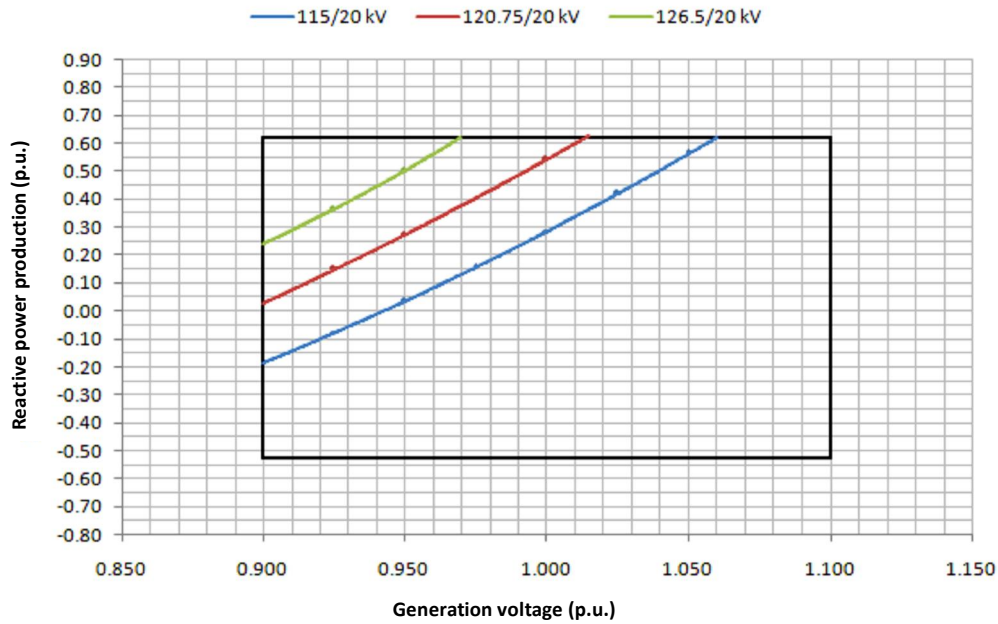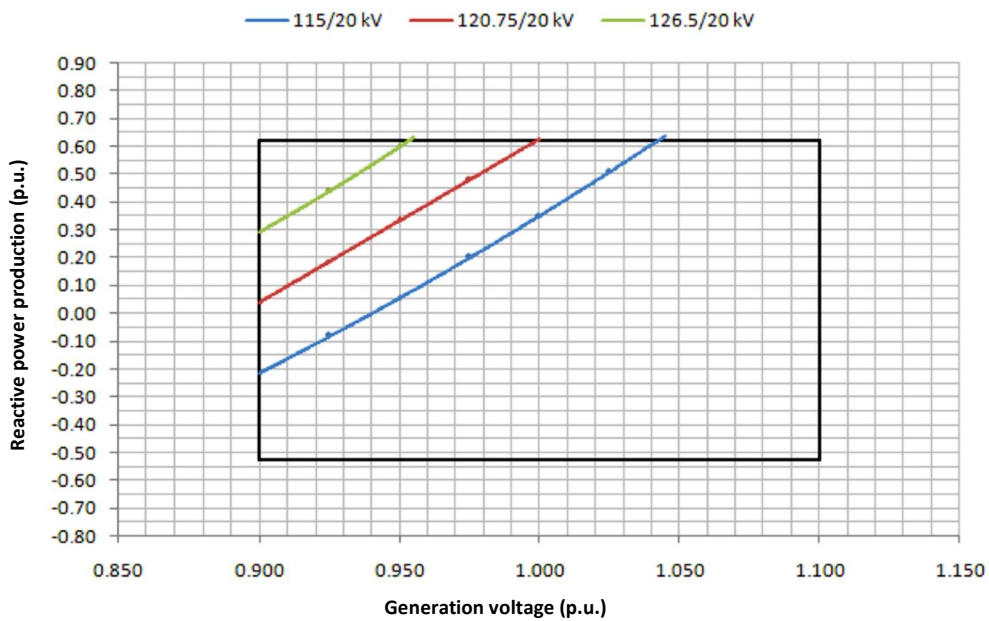**Figure 5**: Qg = f(Ug) and U110 kV = f(Ug) correlations for WT1

Figure 6: Qg = f(Ug) and U110 kV = f(Ug) correlations for WT2

The short circuit currents analyses have to prove that the selected power equipment have to withstand in the extreme conditions of failures, as long as protection equipment clear a fault. The Grid Codes for the TSO and DSO assigned limits for the short circuit currents for all voltage levels. So, the maximal allowed current for 110 kV voltage level is 31,5 kA and for 20 kV voltage level is 16 kA.

The Table 1 presents the output reports from the three-phase short circuit calculations at 110 kV and 20 kV busbars, the closest to WT 1 and WT 2. The report provides and the contributions to the total short circuit current from the adjacent branches/transformers, also.

```
.              PSS/E  SHORT  CIRCUIT  OUTPUT                    HOME  BUS  IS   14161.
.                                                              GACKO          110.00.
.                                                                                     .
. *** FAULTED BUS IS:  14161 [GACKO         110.00] ***             0 LEVELS AWAY   .
AT BUS  14161 [GACKO         110.00] AREA    30  (KV L-G) V+: /  0.000/    0.00

THEV. R, X, X/R: POSITIVE  0.06102  0.19983    3.275

                                          T H R E E   P H A S E   F A U L T
X--------- FROM ----------X AREA CKT   I/Z      /I+/    AN(I+)    /Z+/    AN(Z+)  APP X/R
 14103 [BILECA      110.00]   30 1  AMP/OHM   2262.8   -86.12    16.98   73.19    3.311
 14160 [GACKO_20KV  20.000]   30 1  AMP/OHM    380.4  -102.37     1.19   87.46   22.576
                     TO SHUNT   (AMPS)     0.0     0.00
             TOTAL  FAULT  CURRENT  (AMPS)  2630.1   -88.44

--------------------------------------------------------------------------------
.              PSS/E  SHORT  CIRCUIT  OUTPUT                    HOME  BUS  IS   14185.
.                                                              WT1_20 KV   20.000.
.                                                                                     .
. *** FAULTED BUS IS:  14185 [WT1_20 KV    20.000] ***             0 LEVELS AWAY   .
AT BUS  14185 [WT1_20 KV    20.000] AREA    30  (KV L-G) V+: /  0.000/    0.00

THEV. R, X, X/R: POSITIVE  0.12495  0.46383    3.712

                                          T H R E E   P H A S E   F A U L T
X--------- FROM ----------X AREA CKT   I/Z      /I+/    AN(I+)    /Z+/    AN(Z+)  APP X/R
 14160 [GACKO_20KV  20.000]   30 1  AMP/OHM   4484.1   -86.16     1.01   52.60    1.308
 14183 [WT1          0.4000]   30 1  AMP/OHM   1567.1  -104.98     0.00    0.00    0.000
             TOTAL  FAULT  CURRENT  (AMPS)  5988.8   -91.00

--------------------------------------------------------------------------------
.              PSS/E  SHORT  CIRCUIT  OUTPUT                    HOME  BUS  IS   14186.
.                                                              WT2_20KV    20.000.
.                                                                                     .
. *** FAULTED BUS IS:  14186 [WT2_20KV     20.000] ***             0 LEVELS AWAY   .
AT BUS  14186 [WT2_20KV     20.000] AREA    30  (KV L-G) V+: /  0.000/    0.00

THEV. R, X, X/R: POSITIVE  0.11625  0.43405    3.734

                                          T H R E E   P H A S E   F A U L T
X--------- FROM ----------X AREA CKT   I/Z      /I+/    AN(I+)    /Z+/    AN(Z+)  APP X/R
 14160 [GACKO_20KV  20.000]   30 1  AMP/OHM   4897.3   -86.61     0.79   49.55    1.173
 14184 [WT2          0.4000]   30 1  AMP/OHM   1561.0  -105.45     0.00    0.00    0.000
             TOTAL  FAULT  CURRENT  (AMPS)  6394.7   -91.13
```

Table 1: The output reports from the short circuit calculations at 110 kV and 20 kV busbars

The short circuit current analysis proves that integration of new power facilities (WT1 and WT2 with block transformers and 20 kV distribution lines) will not increase short circuit power level in the local grid, significantly. The short circuit currents are below maximal allowed level, so no need reinforcements in power equipment.

- TEST OF MAXIMAL INSTALLED ALLOWED POWER

The responsible DSO, when estimate connection of small-scale generators, requires the test of allowed production power. In formula, the total installed power S_{inst} has to be less then $S_{sc}/50*k$,

$$S_{inst} \leq S_{sc}/50 \cdot k, \text{ where is}$$

S_{inst} – the total installed power in the connection point,

S_{sc} – the short circuit power in the connection point,
k – coefficient dependent on maximal starting generator current, k=1 for the synchronous machines with salient pole.

The connection point of WT 1 and WT 2 is 20 kV busbar in TS 110/20 kV Gacko. The short circuit power in this point is 294 MVA, the total installed power is 1.6 MW. Checking the test:

$$1.6 = S_{inst} \leq S_{sc}/50 \cdot k = 294/50 \cdot 1 = 5.8,$$

it shows that installed WT 1 and WT 2 are being fulfilled the test of allowed production power.

- POWER QUALITY

A voltage fluctuation in frequency range of 0 - 25 Hz, can be recognized as irritating oscillation of lightbulbs light, is called flickers. Flickers can be caused either in normal wind turbine operation or during power equipment handling. For these wind turbines, the power quality depends on AC/DC/AC convertor, predominately.
The flickers coefficient C_f tells about wind turbine ability to produce flickers. This coefficient depends of wind speed, phase angle of equivalent network impedance, wind turbine installed power and short circuit power. The C_f is provided by the wind turbine producer, or responsible independent institution, based od typical testing of a wind turbine with same or similar characteristics as wind turbine in construction. The wind turbine producer has provided the table of flickers emission for the various average wind speed, phase angle of equivalent network impedance and short circuit power.
After construction completed, the on-site measurements in real operation conditions have to prove guaranteed C_f values. The responsible DSO requires $C_f \leq 20$, what these WT1 and WT2 have fulfilled.

A Voltage Total Harmonic Distortion (THD)(%) is contribution rate of sinusoidal frequency parts which are product of elementary sinusoidal voltage harmonic frequency. According to the responsible DSO Grid Code:

$$THD(\%) = \frac{100}{U_1} \sqrt{\sum_{h=2}^{40} U_h^2}$$

where U_1 is voltage of elementary order and U_h voltage of h-order,

$$U_h = \left| Z_{net,h} \right| \cdot I_h$$
$$\left| Z_{net,h} \right| = \sqrt{R_{50}^2 + \left(2\pi f \cdot L_{50}\right)^2}$$

where $\left| Z_{net,h} \right|$ is absolute impedance value, R_{50} and L_{50} are values in the Point of Common Coupling (PCC) what can be obtained from power flow calculations.
The h-order harmonic current value I_h can be obtained as:

$$I_h = (I_h/I_n \, [\%])/100 * I_n,$$

where (I_h/I_n [%]) is harmonic value, provided from the wind turbine producer table and I_n is nominal wind turbine current.

The responsible DSO allows maximal THD of 6.5 % for the MV distribution grid. The calculations performed prove that WT1 and WT2 produces THD lower then maximal allowed.

- STABILITY CALCULATIONS – SMALL SIGNAL STABILITY

The system ability, affected by small disturbances, to stay in synchronism is called static stability or small-signal system stability. These small disturbances in a power system are very often phenomenon, and can be caused by small variations in power consumption or production.
As the consequences, there could occur:

√ Continuous rotor angle increase caused by insufficient synchronous momentum component,
√ Rotor oscilla ons with higher amplitudes caused by insufficient damping momentum component.
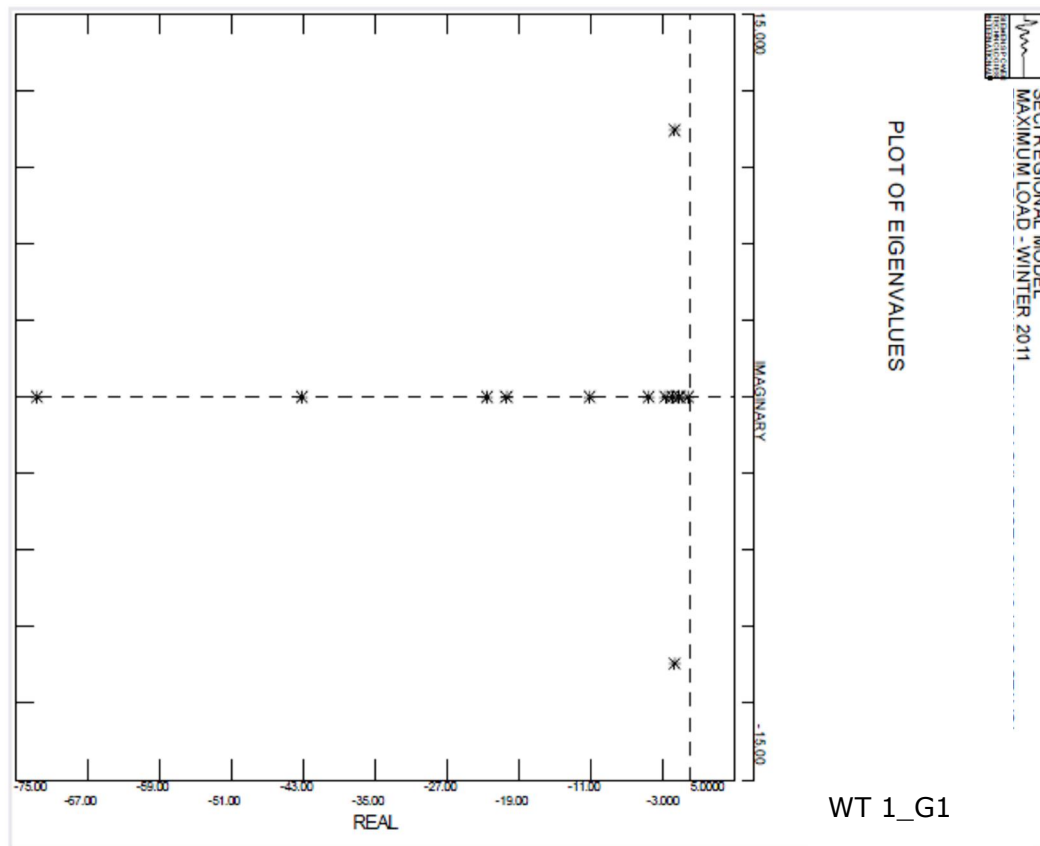

Figure 7: The eigenvalues of G1_WT1

The system response on small disturbances depends on many factors, stationary operation state/point, power system characteristics, synchronous generator exitation current regulation, etc. In most of cases, the problem of small disturbances are dependent on a damping momentum component.

Static stability of a power system is analyzed by system eigenvalues matrix in normal operating conditions. If the real parts of eigenvalues are negative, the analyzed system is considered as static stable.

It is not convenient that stability issues are scrutinized for small-scale wind power integration, nor DSOs require that. Nevertheless, static stability analysis is performed in this case, so Figure 7 and Figure 8 present eigenvalues of WG 1 and WG 2, tested when WG1 is on and WG2 if off (Figure 7) and vice versa in Figure 8. These Figures show that the real parts of eigenvalues are negative, so each generator is static stable for the analyzed cases.
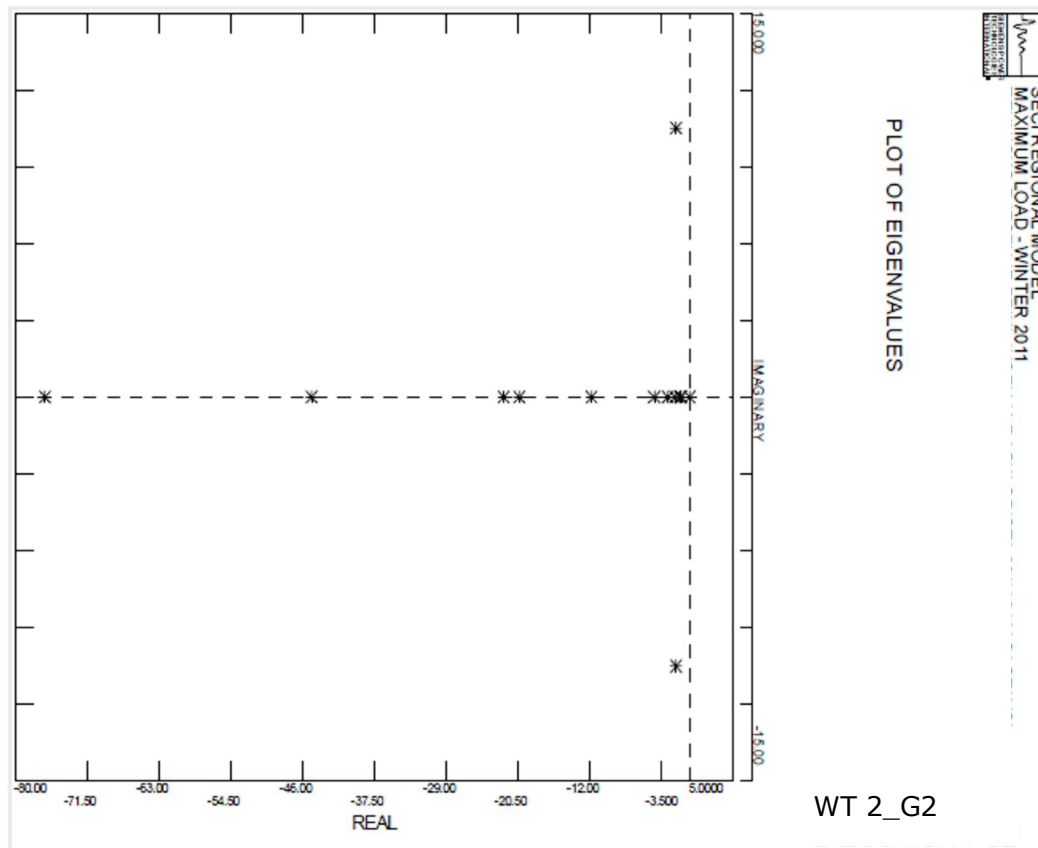

Figure 8: The eigenvalues of G2_WT2

Conclusion

The STSM in EKC have fulfilled my expectations, totally. The experts from EKC have dedicated a lot of time with me, and shared the extensive knowledge and experience they had obtained. The expertise in small-scale wind power generation integration into power distribution grid is part of TU1304 WINERCOST COST Action objectives. This STSM will contribute to overall knowledge I've gained participating in this COST Action and to my proffesional expertise, generally.
The software tools, I've introduced, have helped me to better understanding of specific tasks and therefore to have better task approach and solution.
Also, I am now in position to transfer knowledge and experience from host institution to my colleagues in my home institutions.
During the STSM, I've introduced several professional contacts what could result in further cooperation in some perspective projects/study, in future.