DIVERGENCE OPERATOR FOR A NOVEL POWER SYSTEMS REGULATION

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ABSTRACT

In the present study divergence operator is exploited with the aim to improve the dynamic behaviour of a distribution network weakly connected to the transmission grid. A novel regulator has been investigated to drive a storage device with the target to reduce disturbances affecting the power exchanges with the high voltage power system. The proposed approach has been tested exploiting the DIgSILENT software capabilities. The performance of the divergence based regulator has been evaluated with respect to a traditional frequency regulator response (based on local measures).

INTRODUCTION

One of the most challenging targets for today’s power systems is to integrate an increasing quantity of energy production from Renewable Energy Sources (RES), despite the unpredictability characterizing RES, which makes them not easily manageable.

A possible solution for this problem is the adoption of storage devices able to increase the power systems ability to accept these types of energy sources and to improve the system stability in their presence [1].

The mentioned improvements can be achieved absorbing or injecting energy in the network at the right time. However, this operating mode requires the specification of appropriate techniques for the storage device control [2]. To this purpose, the present study aims at exploiting a storage device control based on the divergence operator [3] [4], with the target to reduce disturbances involving a Medium Voltage (MV) distribution grid with dispersed generation.

The reference scenario of the the work regards scattered users, fed by a MV network weakly connected to the transmission system (i.e. busses with low short-circuit power) in presence of un-controllable and un-programmable generators (e.g. wind turbines subjected to frequent changes in torque applied to their shafts).

Usually the frequency regulation is based on local measures; using this approach to control the storage device can lead to limited performances for MV distribution networks, especially in presence of significant fluctuating generation from renewable sources. Moreover, in order to reduce the economic costs (i.e. to reduce the size of the storage system), an optimized control assumes a significant relevance.

The tests, carried out by DIgSILENT software, are classifiable in three different types, according to the regulation applied to the system:

- no regulation device;
- regulation device driven by divergence operator;
- regulation device driven by pulsation at the terminals of a generator.

The performance of the different solutions is evaluated referring to the disturbances transmitted on the whole High Voltage (HV) system. In particular, it is assumed that lower power flows oscillations acting on the external grid result in an improved electrical system dynamic behaviour.

THE TEST NETWORK

A MV distribution network (radial type) connected to the HV system through the interposition of an HV/MV transformer (Fig. 1) is assumed.

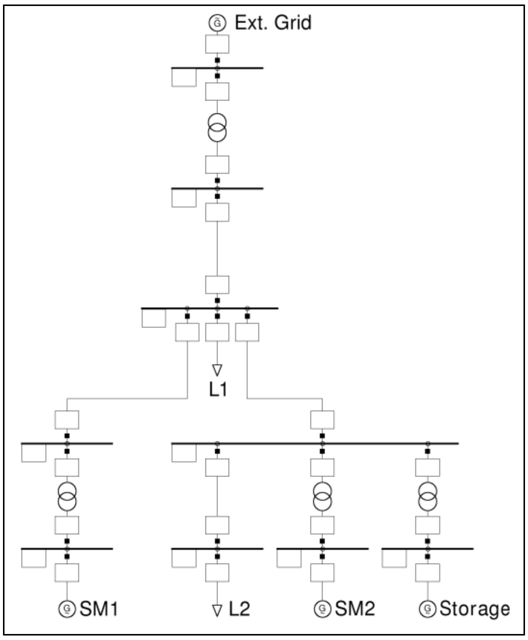

Fig. 1. The MV distribution network adopted for the tests.

Moreover, two wind generators are connected to the grid through 20/0.69 kV transformers. Each generator is composed of a wind turbine and a Synchronous Machine (SM) with rated power equal to 3 MW (electrical machines of relatively high rated power are necessary to highlight the effects they induce on the overall power system, nevertheless the generators adopted are compliant with the connection to a MV network). The SM excitation is realized by permanent magnets and frequency regulation devices are excluded.

Finally, the presence of two loads (L1 and L2) is assumed; they absorb a constant amount of power (for each equal to 2 MW with power factor 0.9 inductive), also when the voltage at their supply terminals varies [5].

The regulator introduced acts on a storage device (installed on the same network's bus of the SM2) capable to absorb/inject power as needed. This is modelled by a fast-dynamic synchronous generator able to deliver up to ±0.15 MW (i.e. the ±5% of the power rating of each generator: beyond that threshold the regulator saturates).

DIVERGENCE OF THE SYSTEM

The divergence of a dynamic system is a scalar quantity defined as the sum of the diagonal elements of the system Jacobian; it measures the rate of expansion or contraction of the state space volume, which is related to the changes of the total energy [6] [7].

Being the divergence a local property which is preserved under phase space reconstruction, it has several features that make it particularly appropriate for transient dynamic systems, as electrical networks. Furthermore, it can be reconstructed from experimental data, without the need to know the differential equations of the system [6][7] using the embedding theory.

However, due to the simplicity of the grid's model implemented and to the knowledge of its differential equations, in this analysis the exact mathematical formulation, explained in the following, has been adopted. The overall system's divergence is the trace of the ODEs set's Jacobian previously mentioned. Consequently, it is the sum of the divergence of each machine, reported in p.u. with respect to the "benchmark" divergence, i.e. the divergence that alternators show at the steady-state (rotational speed equal to ω_0):

$$|Div| = \left| \sum_n \frac{\sqrt{\left(\frac{R_{sn}}{L_{sn}}\right)^2 + \left(j\omega_n\right)^2}}{\sqrt{\left(\frac{R_{sn}}{L_{sn}}\right)^2 + \left(j\omega_0\right)^2}} \right| \tag{1}$$

Where:

- R_{sn} is the stator resistance of the n^{th} generator [mΩ];
- L_{sn} is the stator inductance of the n^{th} generator [mH];
- ω_0 is the nominal pulsation of the network, equal to $2\pi 50$ [Hz];
- ω_n is the actual pulsation of the n^{th} generator [Hz].

From Eq. (1) it can be observed that, in the proposed model, since the resistance and the inductance of the machines are constant, as well the nominal pulsation of the network, only the generators' mechanical speeds variations affect the divergence.

At steady-state condition the divergence so calculated is constant and equal to 1. In presence of a disturbance it varies, being influenced equally by speed variations of all the generators connected to the network. This makes the divergence a global system's stability indicator able to detect the dynamics of all the involved dispersed generation.

TESTS

As mentioned above, the model realized has been used to test performances of the proposed power systems regulation in presence of different types of torque's disturbances. The benefits are evaluated in terms of impact reduction that the disturbances involving the MV network have on the HV system and, with respect to a different point of view, in terms of less stress (i.e. maximum exchanged power) affecting the storage device (that is, at equal disturbances reduction, proportional to the economic cost of the storage apparatus).

It is supposed that the system is initially in a steady-state equilibrium condition, with constant torques (equal to the rated values) applied to the SMs' shafts.

In each test, the type of disturbance to apply to the wind generators has been chosen with the purpose of highlight from time to time the system's properties of interest. Therefore, the typical disturbances introduced by the wind (stochastic variations) have not been used, but rather simpler torque's variations have been taken under consideration. In detail in the tests carried out the following disturbances have been applied to the SMs' shafts:

- 10% step reduction of the torque applied to SM2;
- 10% step reduction of the torque applied to SM1;
- anti-phase sinusoidal torque variations on both SMs (amplitude 10%; period 5s).

Step variation of the torque applied to SM2

A first test is devoted to highlight the effects of the regulator in presence of a step variation of the torque applied to the SM2. At the time t=1 s it goes from the rated value to its 90%, while the torque of the SM1 remains constant and equal to 1 p.u..

Due to the reduction of the power supplied by wind generators, the power flows involving the external grid increase with a damped oscillatory behaviour (Fig. 2). The introduction of a regulator allows to considerably reduce the disturbances involving the HV electric system: in fact, the worst power flows oscillations occur in its absence (blue characteristic). Both the considered types of regulator, driven by the divergence (red) and based on local quantities (green), offer similar performance. Anyhow, in this case, the power flows damping using local quantities is slightly better than the performance obtainable with the divergence operator. In fact, being the disturbance directly applied to the SM to which the local regulator refers, and being the regulator controlled by the SM electrical pulsation, a regulation based on local quantities maximizes the storage action. This is due to the fact that the frequency at the SM's terminals is the network's quantity most sensitive to the perturbation caused by the torque variation.

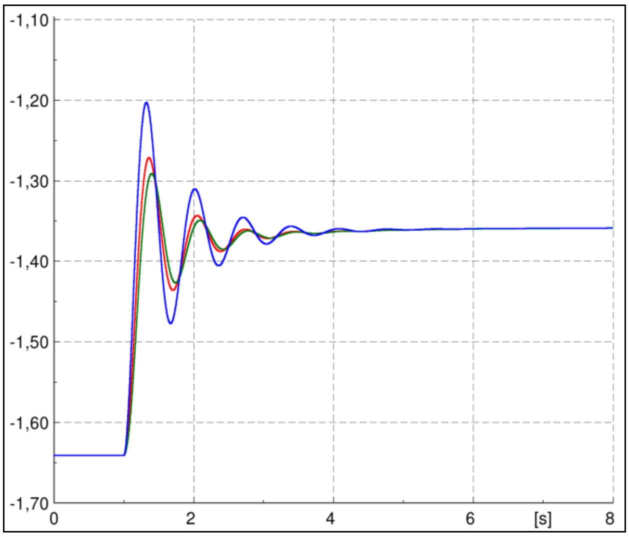

Fig. 2. Power supplied by the external grid during a 10% step reduction of the torque applied to SM2 [MW].

Step variation of the torque applied to the SM1

The analysis of the power exchanges with the external grid has been repeated, using the same modalities of the previous test, but applying the 10% torque step to the SM1 shaft.

The effects on the power flows involving the external grid are reported in Fig. 3. First of all, it's possible to observe that, in absence of a regulator, oscillations interesting the power supplied by the external grid are quite similar to those of the previous test (blue characteristic). This is due to the fact that the SM1 and the SM2 have the same rated power. So, a torque reduction of 10% of the rated value causes in both the situations a similar lack of power (approximately equal to 0.3 MW).

Moreover, it is noticeable that, also in this test, the introduction of a regulator ensures an improvement of the power flows damping. But, contrary to the test in which the torque variation has been applied to the SM2's shaft, in the present situation best results are offered by the regulator driven by the divergence operator (red).

This test shows the limits of the regulator based on local quantities (green): if the torque variation is applied to the other SM, the regulator based on local quantities (the SM2 electrical pulsation) perceives only indirectly the disturbance (in particular, through the frequency oscillations at the terminals of the SM2 caused by the fluctuations of the SM1). Consequently its action is less effective than the effect of the divergence regulator.

The examples introduced are quite simple and useful to detail the characteristic of the proposed approach: the divergence operator is able to take into account the whole dynamic response of the distribution network in analysis, driving consequently the storage apparatus.

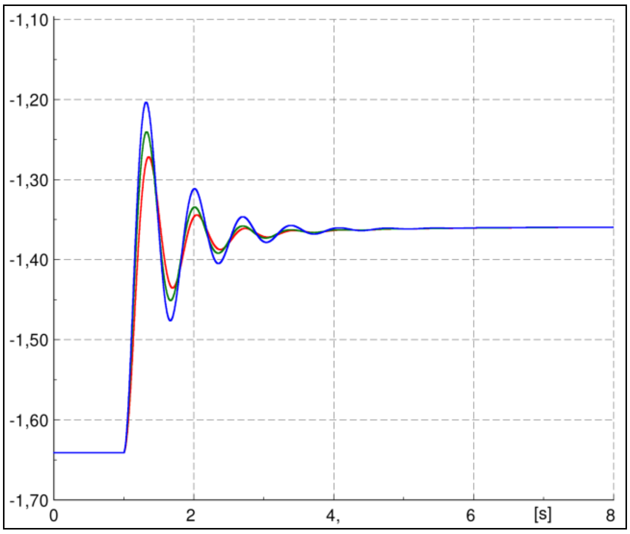

Fig. 3. Power supplied by the external grid during a 10% step reduction of the torque applied to SM1 [MW].

Torque's Sinusoidal Variation

In this test, two sinusoidal torque disturbances have been applied to both the wind generators. They have identical amplitudes (10% of the generators nominal torque) and frequency (0.2 Hz; a frequency value so low is chosen in order to excite the SMs dynamics), but they are in anti-phase.

The particular torque characteristics have been adopted to consider the most critical case for the regulators. In fact, this kind of torque oscillations applied to the generators causes equal and opposite variations of the power injected in the network. The effects of the two machines tend to compensate one each other, therefore the system does not require further injections/withdrawals of active power (the natural power exchange between the two SMs is exactly what is needed to both to damp their fluctuations). As a consequence, it is appropriate that the storage device isn't unnecessarily stressed injecting/withdrawing energy.

The regulators considered react in different ways to these sinusoidal disturbances (Fig. 4): while the resulting divergence of the system differs little from the nominal value, the SM2 terminals' frequency varies according to the torque variations. In the first instance, the power exchanges are very limited (red characteristic) and, when the transient is over, approximately equal to zero. On the other hand, the amount of power injected/absorbed using a regulator based only on the SM2's electrical pulsation is not negligible (green): the peak value is about 20% of the storage device rated power. The regulator perceives only the frequency variations of the SM2, so the injection characteristic has the same profile of that quantity.

Observing the power exchanges with the external grid

(Fig. 5) it is possible to note how the adoption of the regulator driven by the divergence (red characteristic) does not introduce perceptible improvements in the dynamic behaviour of the system, if compared to the case without regulator (blue). Therefore, unlike the regulator based on local quantities (green), it doesn't cause a worsening of the power flow fluctuations.

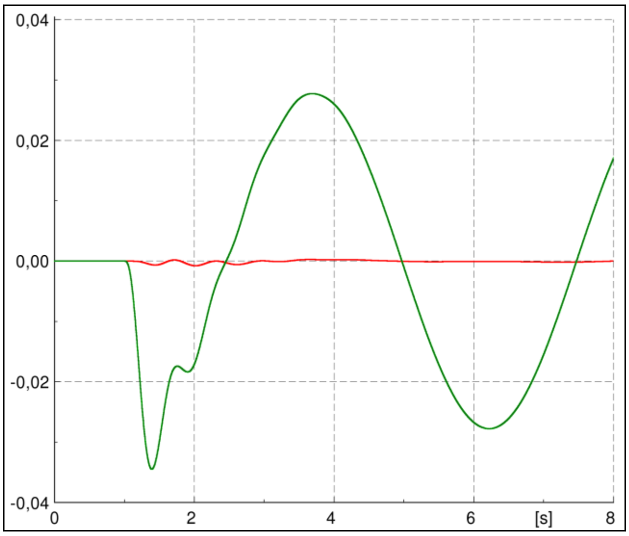

Fig. 4. Power supplied by the storage device during a sinusoidal variation of the torque applied to the SMs [MW].

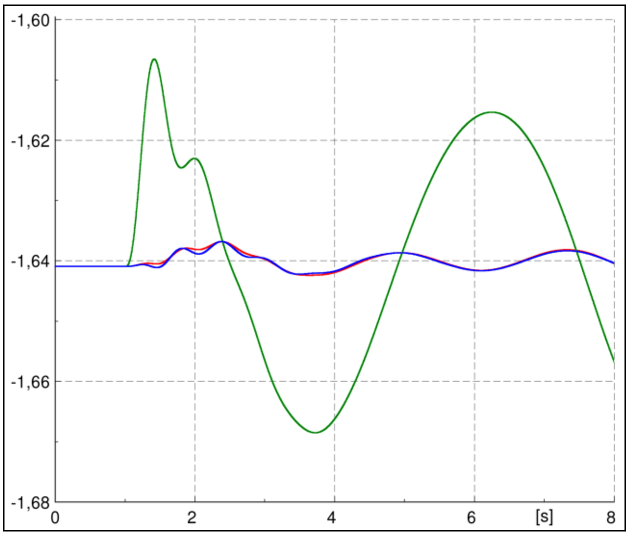

Fig. 5. Power supplied by the external grid during a sinusoidal variation of the torque applied to the SMs [MW].

CONCLUSION

In this study a DIgSILENT model to represent an electrical power system made up of a MV microgrid connected to the HV network has been developed. The model has been used to evaluate the effectiveness of the divergence as indicator to perform a regulation aimed at reducing perturbations, originated on MV network and involving HV system. Its performances have been compared with those of the regulator driven by local quantities.

The comparison has shown that the use of the divergence operator ensures significantly better results. A regulation made using only local quantities, in fact, allows maximizing benefits for the electrical system only when disturbances occur on the reference generator. So, in the case of torque disturbance occurring on that machine, this regulation is capable to obtain a slightly better damping of perturbations involving HV network than using the divergence. However, when torque disturbances affect other generators, it intervenes only marginally on the disturbances reduction.

Moreover, it has bad performances in the situation where the perturbances affecting the dispersed generation are not coordinated (e.g., when they induce some generators to accelerate and, at the same time, others to slow down). In fact, the traditional regulator tends to absorb/inject electric power, causing unnecessary energy exchanges with the HV system and stress for the storage device. The regulator driven by the divergence will instead be able to avoid that phenomenon, not intervening in a situation like this, allowing the generators to exchange the electrical energy needed to come back to the synchronism speed.

Finally, it is necessary to consider that the benefits obtained using divergence can be improved increasing the storage device size adopted (w.r.t. the generators rated power).

REFERENCES

[1] Y. Iijima, Y. Sakanaka, N. Kawakami, M. Fukuhara, K. Ogawa, 2010, "Development and Field Experiences of NAS Battery Inverter for Power Inverter for Power Stabilization of a 51 MW Wind Farm", *Proceedings IPEC 2010*, Sapporo (Japan).

[2] D. Falabretti, M. Merlo, M. Delfanti, J.M. Zaldívar, F. Strozzi, 2009, *Analysis of the divergence operator for the assessment of the stability of a microgrid weakly connected to the power system or islanded*. Available: http://www.manmadenet.eu/output/D5_5_Final.pdf

[3] S. Teleke, M. E. Baran, S. Bhattacharya, A.Q. Huang, 2010, "Rule-Based Control of Battery Energy Storage for Dispatching Intermittent Renewable Sources", *IEEE Transactions on Sustainable Energy*, vol. 1, n. 3.

[4] M. Delfanti, D. Falabretti, M. Merlo, F. Strozzi, J.M. Zaldívar, 2010, "Divergence Operator for the Stability Assessment of a Microgrid Weakly Connected to the Power System", *Proceedings ICHQP 2010*, Bergamo (Italy).

[5] P. Kundur, 1994, *Power system stability and control*, McGraw-Hill.

[6] J. Bosch, D. Kerr, T. J. Snee, F. Strozzi, J. M. Zaldívar, 2004, "Runaway detection in a pilot plant facility", *Ind. Eng. Chem. Res.*, 43, 7019-7024.

[7] F. Strozzi, J. M. Zaldívar, A. Kronberg, K.R. Westerterp, 1999, "On-line runaway prevention in chemical reactors using chaos theory techniques", *AIChE J.*, 45, 2394-2408.