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LOAD BALANCING STRUCTURE FOR MULTIPLE SOURCES SYSTEMS

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Rezumat. *Lucrarea prezintă o structură de control pentru (re)balansarea sistemelor formate din generatoare/surse multiple, cu scopul menținerii constante a ieșirii globale, în condiții de funcționare defectuoasă sau perturbată. O astfel de structură de control își dovedește aplicabilitatea în cazul sistemelor formate dintr-un număr redus (trei, patru) de surse de producere a energiei, conectate în paralel, situație întâlnită din ce în ce mai des în zilele noastre, în special în structurile de tip smart grid sau, în industria energiei regenerabile (eoliană, solară) etc.*

Abstract. *Current paper presents a structure to (re)balance a multiple sources and/or generator control system on maintaining the global load, in case of charge and functioning disturbances. Applicability is proved on a control structure of the three and four sources connected in parallel to provide energy, a situation that has been encountered more and more these days especially in the smart grid or renewable energy industry (wind, solar and small generators), etc.*

Keywords: balancing; control performances; control architectures; disturbance rejection, renewable energy

1. Introduction

It is well known that the use of conventional technology to produce electrical power normally results in pollution that affects everyone. It often relies on the burning of fossil fuels that produce dangerous gases that often destroy the environment.

So now many countries/companies/communities are turning to energy sources that result from renewable sources.

Meanwhile, the use of renewable sources sometimes, needs special connection to existing distribution network, function on specific introduced disturbances.

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Most actual used renewable energy sources are: solar energy, which uses solar radiation power to produce electricity with photovoltaic equipment; and wind energy sources, which use the wind power. For production of large quantities of energy, necessary e.g. for a small town or a residential area, these sources are grouped in plants in geographical areas with energy potential.

These multi systems have a discontinuous function; they are dependable of wind and sunlight; so the production needs to be load balanced using some alternative sources to assure a global output. To optimize in real time function there are systems that are used like some balanced control structure.

The balanced control of two or more sources/generators was and continues to be an important subject in the area of practical applications. With time, various solutions, from simple ones like parallel marking of control loops, to complex structures and systems using, have been implemented and/or just theoretically proposed. The purposes of these solutions are certainly that of increasing performance and quality and secure exploitation of production installation. A very short list of works from this area can include [1-5].

For a multiple generator system to be stable, sometimes it imposes including a storage system to accumulate the surplus energy and/or to reconvert it in when it's needed [6]. Stopping one of the sources can lead to the necessity of compensating the system with another system or with a storage power plant.

To temporarily energy store it can implemented a system with a pumped storage power plant (electricity is transformed into a mechanical energy e.g. by pumping the water through pipes into reservoirs), hydrogen storage from electrolysis system, battery etc.

The main subject of this paper is the Balance Control Structure (BCS), in which the load of each sources need to vary to maintain a precise global output, despite the transitory regime of the set-point, and/ or load disturbances that might occur on the plants.

This mechanism can be applied in a variety of industrial processes such as local/ zonal energy generation.

The paper tries to offer high performance solutions in which the local set-point itself must be modified during the operation (real time). The operations must be developed as fast as possible and with assuring the highest precision of keeping it in the transitory phase that follows the adjustment.

A situation when the set point for a parallel system needed to be rise for maintains a constant output value that can be encountered when a source becomes inactive or is damaged and another source needs to compensate with extra power (see Figure 1).

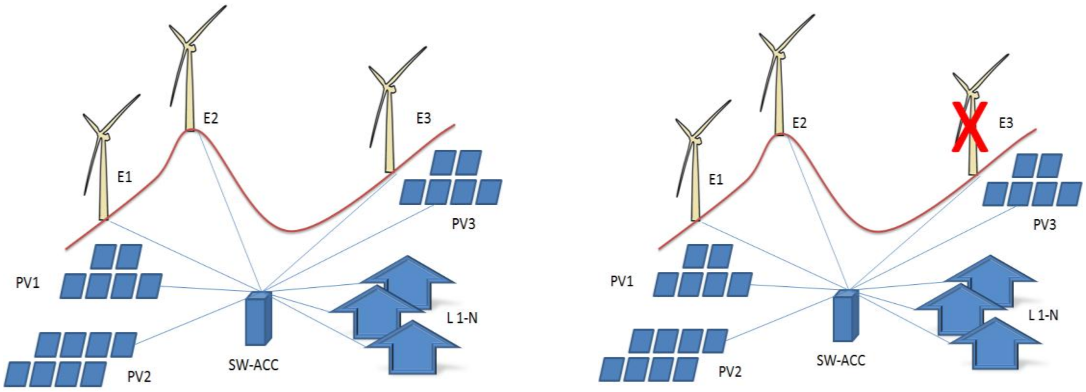

Fig. 1. System with multiple energy sources.

In next figure E1, 2, 3 are Aeolian generators, PV1, 2, 3 are photo-voltaic cells, L1-N are loads and SW-ACC is load balancing structure (eventually wits accumulators).

The tested scenarios include perturbation of control loops, load set points adjustments and compensating the failure/limitation of a source, covering the main critical situations encountered in real exploitation.

2. Load balance methods for multiple sources

2.1. Classic solution

The parallel structures were used for multiple systems for a long time and they have success in many important industrial processes. One of these versions is presented in Figure 2.

On these two parallel (processes) sources structure few (simulation) experiments are developed. The main idea is to produce a certain quantity of energy, but without a compensation method.

The set point for the global parallel systems is de-composed in two ratios (r_1 and r_2), one for each system and the corresponding outputs are y_1 and y_2. This ratios summed need to be 1.

$$a_1 + a_2 = 1 \tag{1}$$

Figure 3 presents the evolution of a transitory regime for set-point changes and the load disturbances. If a source encounters problems this will be immediately "visible" in the global system output.

Used colours are: red – general set point (r), green and purple - processes outputs (y_1 and y_2), blue – global output (y).

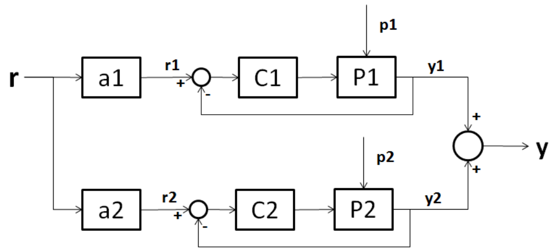

Fig. 2. Classic solution based on parallel connection of two or more sources without compensation.

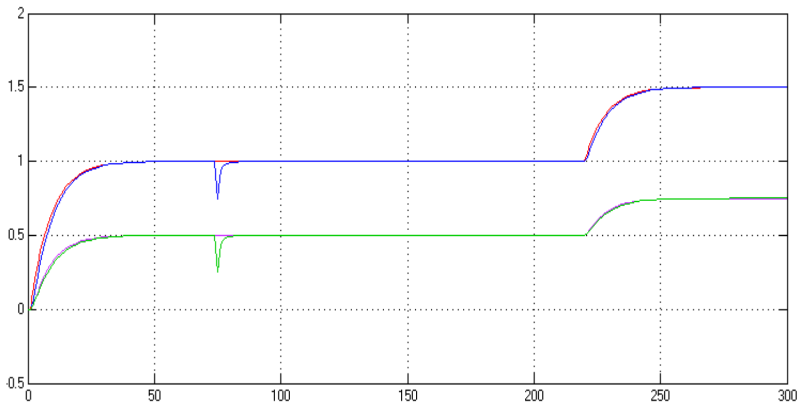

Fig. 3. The proposed generalized solution for a parallel connection of two sources without compensation.

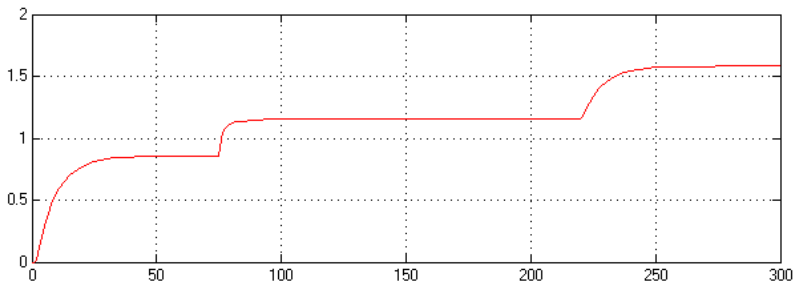

Fig. 4. Integral signed error evolution for two parallel systems without compensation.

To evaluate the performance of the global system, total output error can be the basis of a criterion analysis. For this analysis two methods are used: integral of signed error (see Figure 4) and integral of absolute error.

The global error is calculated using next trivial formula:

$$e(i) = r(i) - \left(y_1(i) + y_2(i)\right) \tag{2}$$

$$ERRs(i) = \sum_{0}^{Ns} e(i), \quad ERRa(i) = \sum_{0}^{Ns} |e(i)| \tag{3}$$

where $i = 0 \div Ns$; Ns is number of samples.

As presented in Figure 4, the integral (signed) global error (*ERRs*) for parallel systems is not 0. Here, one generator fail situation was not tested because there are no possibilities to compensate it and it will increase global error.

2.2. Proposed load balancing structure

A better solution to parallel control of multiple systems is presented in Figure 5. Here the main idea is to add a fraction of the control error as a supplementary set point values to neighbor (parallel) system/generators.

$$r_1 = r \cdot a_1 + e_2 \cdot F_1 \tag{4}$$

F_1 and F_2 are transfer function of just simple constant and have the role to normalize the set point for every generator and to stabilize the system, preventing some auto-oscillation situations.

For a_1 and a_2 is imposed condition is imposed (presented generally in [5]):

$$\sum a_i = 1, \quad \text{where } i = 1, 2, \ldots \tag{5}$$

The output of this multiple generator system is created by the relationship:

$$y = \sum_1^N y_i, \quad \text{where } i = 1, 2, \ldots \tag{6}$$

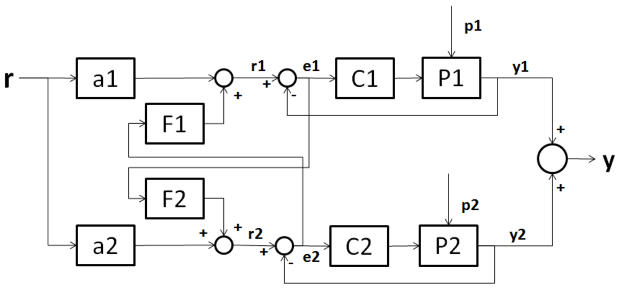

Fig. 5. The proposed solution for a parallel connection of two sources with balance structure.

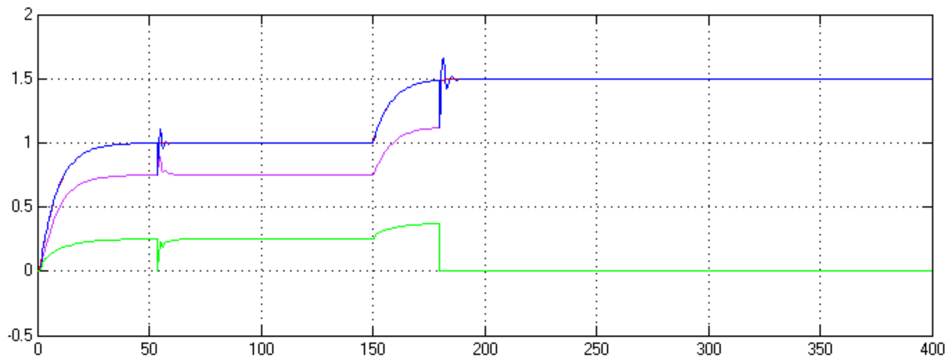

Fig. 6. Output of two parallel systems with compensation.

Using of load balancing structure can compensate disturbances and theoretically, one generator fail or limitation. In reality compensation of one generator fail imposes important "reserve" (e.g. 50% at least for two element structures). If number of parallel generators is bigger is easy to support closing of one of them.

In normal function null error means a null supplementary set point adjustment.

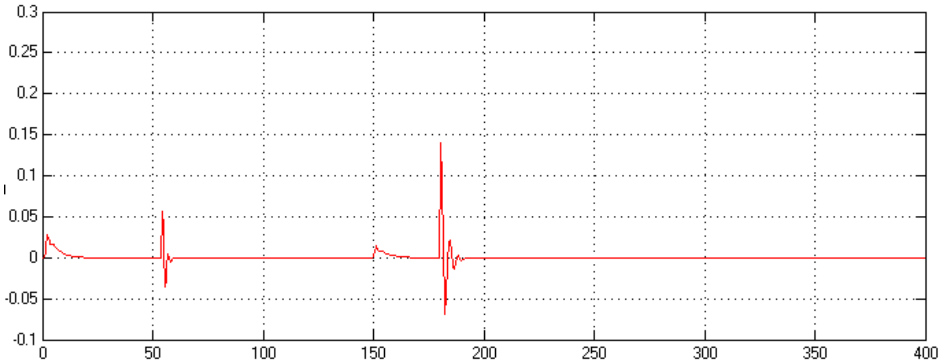

Fig. 7. Signed integral error evolution for two parallel systems with compensation.

From Figure 6, 7 and 8 it can be see that the proposed system is stable and if it encounters some difficulties when a perturbation appears, these are fast rejected cause of the balanced control structure. On sample 60 an error appear on system 2. This moment is "visible" on ERRs and ERRa parameters. On sample 150 general set point changes to 1.5 and on sample 180 system 2 stop (total) and system 1 set point is rebalanced.

If the absolute integral error evolution (see Figure 8) is analyzed it can be seen that every time when one of the systems is disturbed or one source becomes inactive the ERRa rises. Lower finial value means performance (qualitative) system.

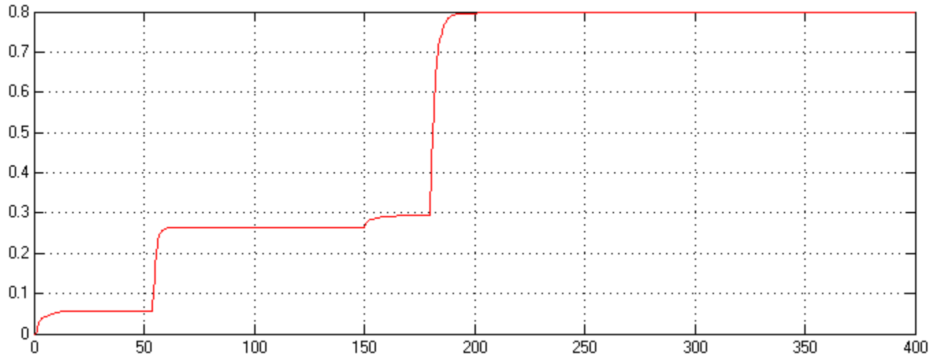

Fig. 8. Absolute integral error evolution for two parallel systems with compensation.

From this point of view the structure has an additional degree of adaptation with F1 and F2 variables. Once again, their role is to normalize the set point for every generator and to stabilize the global system, but at the same time, it can ensure a lower value for the ERRa parameter.

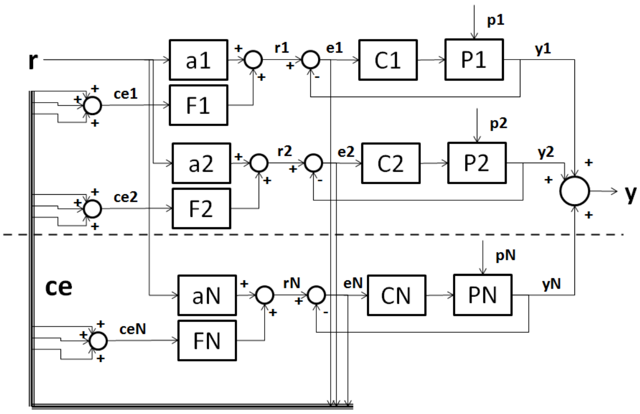

Fig. 9. The proposed solution for a parallel connection of N sources with balance structure.

3. Generalized structure

Figure 9 presents a generalized load (re)balanced structure. Here each set point has similar expression:

$$r_i = r \cdot a_i + ec_i \cdot F_i, \mathrm{i} = 1 \ldots \mathrm{N} \tag{7}$$

where N is systems number and

$$ec_i = \sum_{j=1}^{N} e_j, \mathrm{i} \neq \mathrm{j} \tag{8}$$

ce_i represents correction errors for each systems, and e_i respectively close loop errors for each (load) loop.

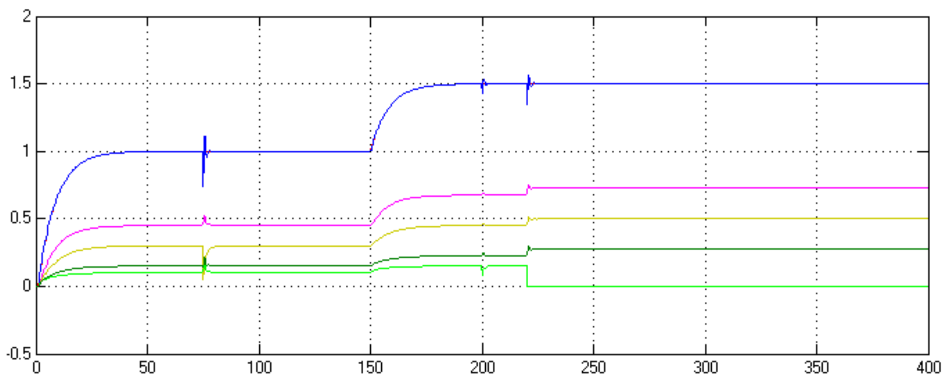

Fig. 10. Output of four parallel systems with compensation.

Proposed structure was tested with three and four parallel systems. The next figures present results for four systems. Same, take two systems simulation on 75 and 200 sample one of the process was disturbed. After systems stabilization, it is considered that the third source fail (sample 220). By doing this, the set point for both functional sources increases and permits the global system to maintain the predefined value for output y.

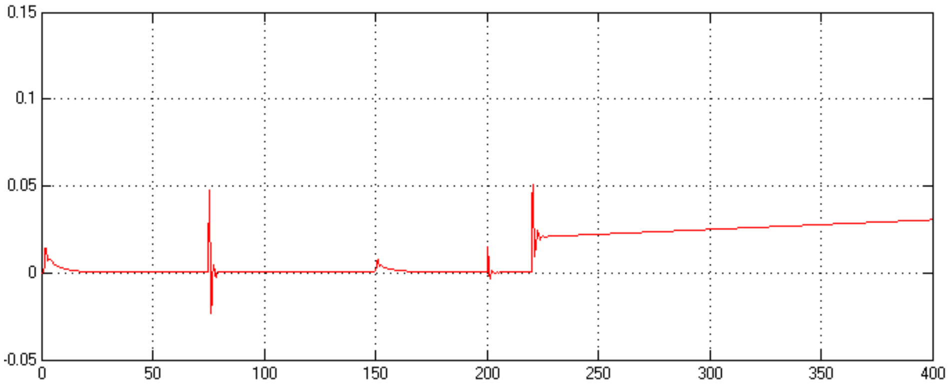

Fig. 11. Integral of signed error evolution for four parallel systems with compensation.

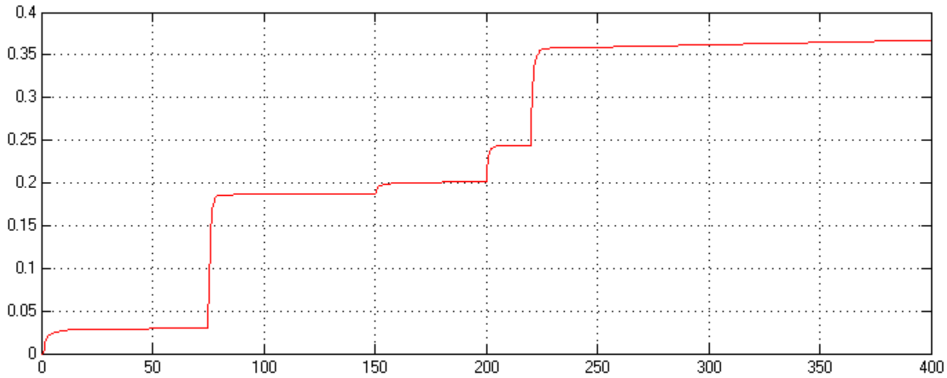

Fig. 12. Integral of absolute error evolution for four parallel systems with compensation.

Simulations for four energy sources offer similar results like two systems case: tracking the set point evolution and successfully reject of the one source fail perturbation. From the signed ratio error integral evolution it is visible that by increasing the number of sources the system provides superior performance – by lowering the error value (see Figures 11).

Good results are obtained for proposed structures for the absolute (modulo) output error integral. These results sustain proposed structure. For raising the system performance some filters can be used for general set point.

To control these multi systems PI, PID or RST [8], [9] algorithm structures can be implemented. Last one can ensure increase qualities or performances.

4. Simulations and real time results

For validating the proposed system performance several diagrams have been implemented in Matlab - Simulink and various evolution scenarios have been imagined. Some of these tests ware already presented in Figures 6, 7, 8, 10, 11, and 12. An example of implemented Simulink structure is presented in Figure 17.

4.1. Real time tests

To complete the Simulink tests, functional experiments were performed during several laboratory tests on a small scale plant. Its purpose was to control the air flow of three separate fans (assimilated as three generators), similar to the Figure 9 situation. It was first implemented a load set point re-balanced structure; here, the control level includes only control loops and the remaining calculation elements are implemented on the supervisory level application.

The plant structure was designed based on three parallel fans (see Figure 13). The connection between the process platform and the computer was made using three National Instruments NI USB 6008 [10] data acquisition devices.

Two real time software applications for control were developed in the National Instruments - LabWindowsCVI package [10]. The first one, Figure 14.a - (Reg_Test_PID_MIX_6008a, b, c) implements a single closed loop control with PID [4] algorithms. The second one – Figure 14.b, (Reg_Test_38_MIX) implements the proposed load re-balanced control structure (presented in Figure 9) and sends set points values for the three closed loops – the first application. Using these software applications there were made a few tests such as set point change, system removing – fail, etc. as presented in the following paragraphs. In all the experiments presented in the next figures, the left side represents the set point and measures evolution - with red color system 1, with blue system 2, with green system 3 and the right side - global error.

Figure 15 represents a normal evolution on 60% global set point position. Imposed ratios for the three generators are 0.45, 0.20 and respectively 0.35. There can be seen that the balancing structure "split" the global set point in 27, 12 and 21 values. After the transitory evolution the error is maintained close to 0. Because tested fans are very sensitive null value is not reached for long time.

Fig. 13. Experimental laboratory platform.

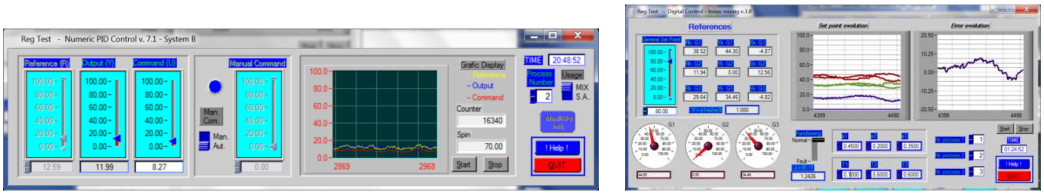

Fig. 14. **a)** single closed loop PID controller; **b)** proposed control structure (variant solution).

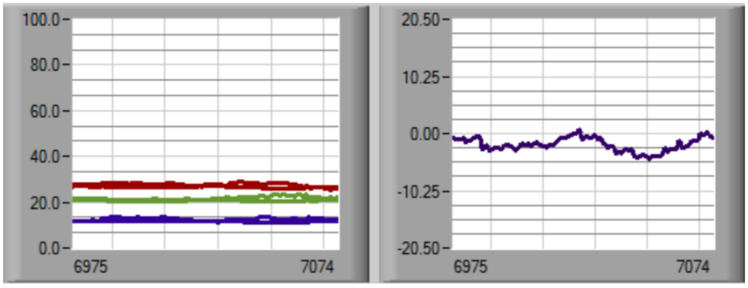

Fig. 15. Real time evolution – 60% normal functioning (left), global error (right).

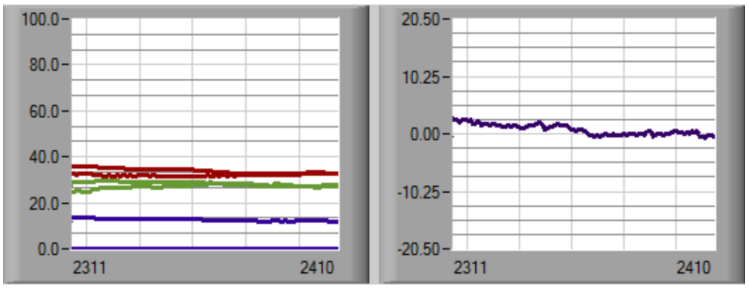

Fig. 16. Real time evolution – 60% fault rejection: ratios change (left), global error (right).

Figure 16 represents system 2 fault evolution on 60% global set point position. Imposed ratios for the three generators are still 0.45, 0.20 and respectively 0.35, but after (re)balancing new set points are about 32.79 (system 1 - red) and 27.16 (system 3 - green) values. The global error is maintained driven close to 0.

On the last test, systems 1 and 3 have enough "reserve" to reach new re-balanced set point (each of them has 0-100% functioning domain). If current position (global set point is high, close to 100%) and ratio coefficients are not close, it could be impossible to reach new set point values.

For all laboratory test F_1, F_2, F_3 are chosen as first order transfer function. On the simulation test, only one of them contains dynamic element (first order element), rest of are simple constant (gain). Meanwhile, gained values are less than 1/(N-1) (N – total number of parallel systems).

Small gain ensures very stable global system, but with long time for disturbances rejection. Big gain (close to 1/(N-1)) choice has short time for disturbances rejection advantages but(!), with auto-oscillations risk. An adaptive solution could be optimal solutions.

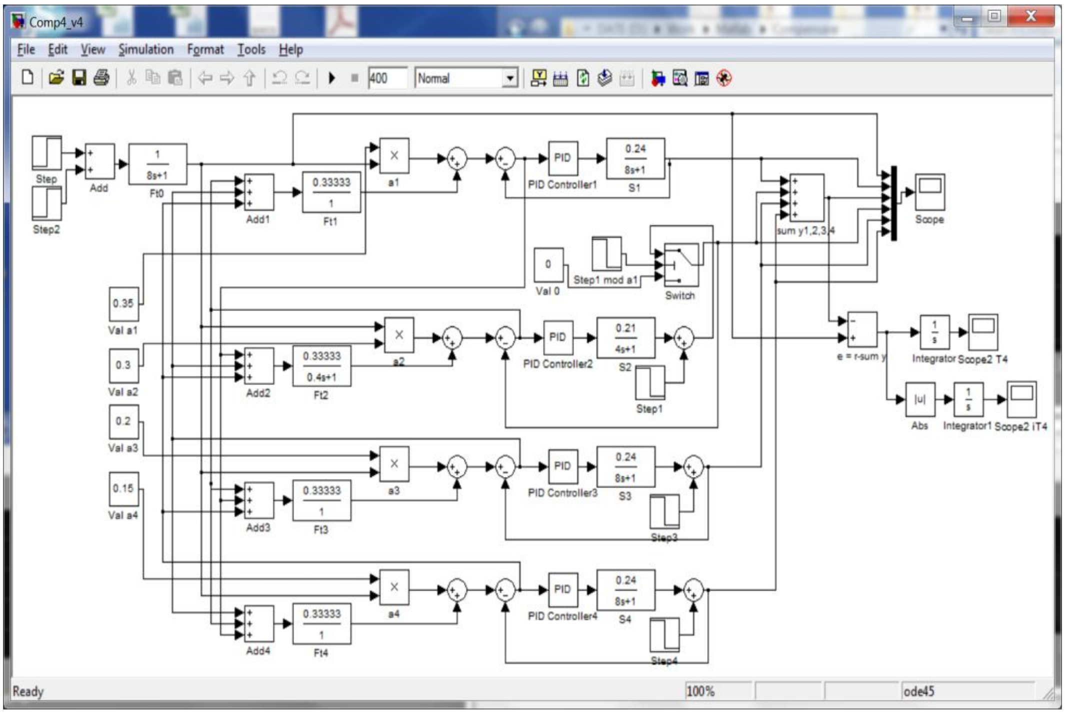

Fig. 17. Implemented Matlab-Simulink simulated structure.

For superior performances about ERRa and ERRs it is recommended to include a filter for global set point, as presented in Figure 17. Brutal changes are important causes for oscillations.

Conclusions

As general conclusion, proposed balancing structure for multiple (parallel) systems are important to compensate the absence or limitation of one or more components and can ensure superior performance versus simple multiple parallel systems.

Meanwhile, re-balancing structure is very simple and is suitable for real time implementation, as presented or real time tests. Depending on process structure [7] and implemented particularities a supervisory or safety level can include it.

Multiple renewable energy producing sources (wind, solar, hydro, thermal etc.) could be one of re-balancing application. Here, the weather's dynamic evolution represents the main disturbances.

In all tests simple PI control algorithms were used, one of used test program is presented in Figure 9. For superior performances (references tracking, disturbances rejection, etc.) there are recommended two degrees of freedoms algorithms, as RST [9].

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