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Storage Selection for DG applications containing Virtual Synchronous Generators

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***Abstract*--The paper is presenting an algorithm for establishing the best types of electrical storages for the virtual synchronous generator (VSG), depending on the application case and desired nominal power of the VSG. The resulting application provides a description of available technologies in terms of characteristics matching the desired properties of the storage in accordance with the scenarios described by the user.**

***Index Terms*-- virtual synchronous generator, storage technologies, system inertia**

I. Introduction. The VSG concept[1]

MODERN technologies deployed by the power systems today make extensive use of power electronics equipment. Moreover, distribution networks design changed as allowing connection of power generators (mostly having as primary energy source renewable energies) at low and medium voltage level, opening in this way the concept of active distribution grids [1]. It is envisaged that in a near future small non-synchronous generation units will replace a significant part of the synchronous power generation capacity, and therefore the total rotational inertia in the system will decrease significantly. One consequence of an ever decreasing share of directly connected synchronous generators to the grid will be the loss of ability to control frequency variations in the classical way, i.e. relaying on longer time constants during various perturbations. Until the whole protection and control concept will manage to cope with the changes into the power system structure, a way to stabilize the grid frequency is to add virtual rotational inertia to the distributed generators. A virtual inertia can be attained for any generator by adding a short-term energy store to it, combined with a suitable control mechanism for its static converter. In this way, a non-synchronous generation unit can behave like a "Virtual Synchronous Generator" (VSG) during short time intervals, and contribute to stabilization of the grid frequency [2-3].

There is a high number of storage applications described in the literature [4-11]. However, in most of the cases, the selection of the storage technology is based on availability and price mainly. The storage parameters and circuit design are usually afterwards derived.

In this paper, a number of characteristics of the desired storage facility, able to describe as accurate as possible all study cases have been derived. There is a small set of additional input variables to all study cases which are needed for the calculation of the characteristic quantities of the desired storage facility. Then the quantities describing the desired storage facilities which have relevance for all storage technologies are selected and appropriate values for each technology are given. A filter algorithm as depicted in Fig. 1 is derived that is able to provide an answer to the question: «which storage technologies best fulfill the specifications “i” derived from the application case “j”?». This filter and its resulting output are implemented in either Matlab [12] or Excel [13].

II. Description of application cases

Case 1: Power balancing with wind turbine in autonomous grid

The system concerns a wind farm with DFIG wind turbines (intermittent, uncontrollable generated power). With the DSO a certain power level is agreed for the next t_{DSO} minutes. The main objective is to keep the rate of change of generated power from the own DG beneath a predefined level.

Case 2: Safety and Security of supply

This case concerns a PV system in a weak or autonomous grid, mainly resistive and capacitive. Faults in a remote feeder may cause voltage variations that determine disconnection of the PV system. The main objective is to ensure continuous operation during the voltage variation.

Case 3: Reconnection of micro grid

This case concerns a set of micro CHP’s without storage that are directly connected to an autonomous grid or weakly connected grid, mainly resistive and capacitive. In case the

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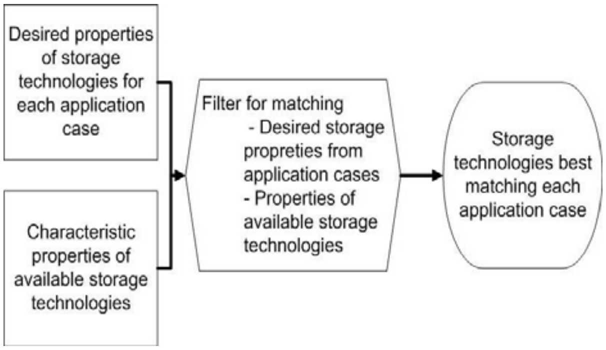

Fig. 1 Storage selection method

micro grid is disconnected from the main grid for several minutes (t_{island}) during a contingency situation in the main grid, the generated power does not match the load and the micro CHPs trip. The main objective is to ensure continuous and stable operation during the island operation while ensuring the reconnection after t_{island}.

Case 4: Coordination of electricity stores

This case concerns a grid with a mix of traditional power plants, DG units interfaced by static converters and VSGs. In cased of severe power unbalance, the VSG's and/or the DSO have to participate in a coordinated action to maintain the power balance for longer duration t_{coord}. The main objective is to ensure compatibility between the various modes of the VSG's in operation, together with development of algorithms for coordinated action of storage devices contained in VSG's, local generators and, loads.

All application cases are divided into sub applications as derived from the maximum power of the loads, P, defining the grid under study.

As in all above described cases the VSG simulates a synchronous machine continuously, this imposes additional constraints to the storage module.

Each case was described by a set of *K* variables; among the more relevant are:

- Maximum power of the loads in the considered grid;
- The power of the controllable generation units, defined by a ratio χ , which best describes a typical network in the power range *P*;
- VSG action time;
- Averaged State of Charge (SOC) at normal operation: according to the intended use of the VSG (support of generation during faults resulting in loss of generating nodes; voltage dip compensation), it appears useful to set SOC to a higher or a lower value;
- Detection time;
- Control delay;
- Maximum total response time delay;
- Maximum number of contingencies per year (the maximum number of events leading to full need (charge/discharge) of the storage capacity; the actual number was derived from multi-annual measurements in a distribution grid in Romania;
- Maximum number of micro-cycles per year (the maximum number of small events in the grid leading to the need of VSG intervention, but with a smaller amount of energy, up to 10% from the maximum state of charge; the actual number is derived from grid simulations).

All cases are described by a set of variables, derived from the above case descriptors in such a way that this set can be directly related to storage technologies. As they will be used in an automatic checking of storage technology availability, an identifier will be attached, in the form of R[equired]P[roperty]k, k=1…20. Some of these properties are listed below:

RP1: type of grid connection. It describes the availability in the PCC of VSG of either an ac or dc connection;

RP2: minimum rated voltage. It describes the minimum voltage in the PCC of the VSG. Usually it is 90% from the rated voltage of the grid where the DG is connected.

RP3: maximum rated voltage. It describes the maximum voltage in the PCC of the VSG. Usually it is 110% from the rated voltage of the grid where the DG is connected.

RP4: minimum time to put store back to SOC_avg (recovery time). It gives the minimum time interval between two consecutive events which requires the VSG operation in 2 different directions (charge/ discharge).

RP5: nominal cycle time. It gives the minimum time interval between two consecutive events which requires the VSG operation. It is based on the worst scenario (storage fully discharged after the first event).

RP6: Access time (delay time) to storage. It is derived from the actual hardware implementation of the VSG: from the response time are subtracted the detection time (according to the available data acquisition system) and control delay (depending on the algorithm to be implemented).

RP7: Minimum number of full cycles that the storage must deliver. It is derived from the assumed number of grid events that would require full storage capability of the VSG, over the whole economical life.

RP10: SOC minimum and maximum (rated).

RP13: Minimum energy density. It is derived from practical considerations: assuming that a conventional generator of rated power 100kW would occupy about 1.5m^3, the minimum energy density is derived.

RP15: Minimum number of micro-cycles that the storage must deliver. It is derived from the number of micro events which describe the network (from simulations) considered over the whole economical life of the VSG.

RP16: Minimum economical life time in normal operating conditions. It is derived from considerations regarding the life time of the DG in each case.

RP17: minimum charging efficiency. It is derived from case definition: the fraction from the duration of VSG action (T_{VSG}), when the storage is charged to SOC_avg

RP18: Maximum self discharge. It is derived from considerations regarding the worst case when VSG has to operate using the full storage, and still be ready to operate in case of a second event.

RP19: Minimum discharging efficiency. It is derived from considerations regarding each case definition.

RP20: Maximum cost of storage per kWh, when compared to a diesel generator [kEuro/kWh]. It allows comparing the cost of storage with an equivalent diesel generator operating over the economical life of the VSG, delivering the equivalent electrical energy to the grid.

III. Description of storage technologies

A set of N variables were selected for describing the known properties of the available storage technologies possible to be considered into the VSG applications. Some of the properties are listed below:

- minimum operating voltage range per commercial unit: the lower limit of the voltage range of the energy storage after commissioning a suitable number of units (cells);
- voltage per cell: the nominal (conventional) voltage value of a single cell of the energy storage, as it is made commercially available;
- maximum current per commercial unit;
- maximum number of full cycles: the number of full cycles of charge – discharge the energy storage unit should withstand during its operating life;
- maximum number of micro cycles;
- minimum and maximum state of charge (SOC rated): values that the energy storage can withstand without permanent damage;
- minimum energy density of a commercial unit per volume;
- minimum charging efficiency at nominal current or power;
- maximum self discharge;
- minimum discharging efficiency at nominal current or power;
- nominal cycle time;
- nominal charging and discharging times;
- round cycle efficiency;
- maximum total response time delay, as the necessary time for the energy storage system to provide the required amount of energy;
- maximum power vs. time, within rated voltage range;
- minimum economical life time in normal operating conditions.

In addition, an economical variable is derived: the minimum cost of storage technology per kWh. It is the ratio of total cost (including converters) and the capacity of the energy storage unit.

IV. Selection algorithm

The selection algorithm of the best available storage technology compares (using the mathematical relation selected or validated by the user) the required property (derived from desired application case) with the corresponding characteristic of each storage technology. Each unsuccessful comparison generates a number equal with the corresponding weight attached to the requirement. Each successful comparison generates a null factor. The weight is selected by the user for each case and each desired property. The sum of all resulting factors is characterizing the degree of non-adequacy of the storage technology to the requirements of the considered application case. Among the storage technologies, that with the minimum factor of non-adequacy is a candidate for the best available storage technology. Further, any combination of two storage technologies can decrease this factor and leads to a better candidate. The algorithm was implemented in Matlab environment (for coping with more detailed models of analyzed cases), see Fig. 2 and Fig. 3. The resulting spreadsheet gathers data from the two tables, verifies the constraints (relations <, >, =) and decides whether a required property of a particular storage is suited for a particular application or not as in Fig. 5. It outputs the total weight factor of the unfulfilled conditions and returns as comments the unfulfilled properties.

There are several options for displaying the result, such as overwriting current results or write them in a new file. The name of the file contains a timestamp. One can choose to see the results for a particular case or only for a lower number of storage options. One can also see the properties that haven't been fulfilled by any of the C_k^2 combinations of the k (1<k<N) selected storage technologies.

The Excel version of the program has been developed in order to make it easy accessible with minimal software requirements and IT knowledge. Moreover, data is more likely to be stored, exported and edited in Excel spreadsheets than in plain text files that the Matlab version uses for inner data streaming routines.

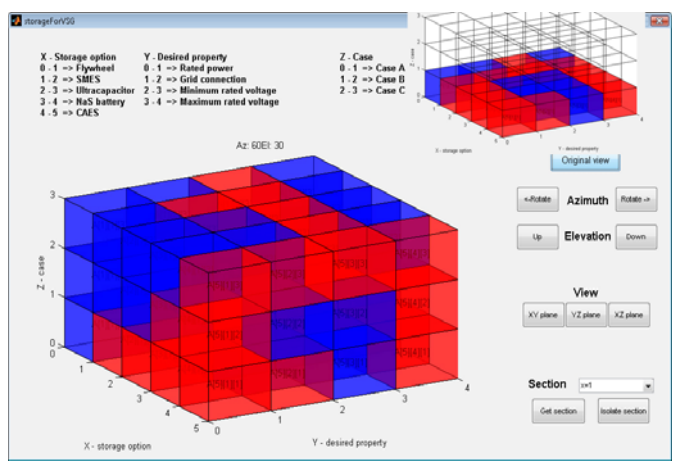

Fig.2 Graphical representation of the storage selection result (in Matlab)

	A	B	C	D	E	F	G	H	I
1	ReqPropID	Property name (from D3.1.)	Unit	Symbol (<, > or equal)	Importance / weight factor	PropID (from D3.2.)	Case 1.1	Case 1.2	Case 1.3
2	1	type of grid connection	dc or ac	equal	0.05	1	1	1	1
3	2	minimum rated voltage	kV	>	0.05	2	0.621	0.621	0.621
4	3	maximum rated voltage	kV	<	0.05	3	0.759	0.759	0.759
5	4	minimum time to put store back to SOC_avg (recovery time)	hr	>	0.05	4	0.5	0.5	0.5
6	5	nominal cycle time	hr	>	0.05	5	1	1	1
7	6	Access time (delay time) to storage	ms	>	0.05	6	20	20	20
8	7	Minimum number of full cyles that the storage must deliver	1	<	0.05	7	202000	202000	202000
9	8	Maximum power vs. time within rated voltage range (diagram)	=	equal	0.05	8	1	1	1
10	9	minimum operating temperature	degC	>	0.05	9	5	5	5
11	10	SOC minimum (rated)	%	>	0.05	10	10%	10%	10%
12	11	maximum operating temperature	degC	<	0.05	11	40	40	40
13	12	SOC maximum (rated)	%	<	0.05	12	95%	95%	95%
14	13	minimum energy density	kWh/m3	<	0.05	13	19.61	19.61	19.61
15	14	round cycle efficiency	%	<	0.05	14	24.9%	24.9%	24.9%
16	15	Minimum number of micro cyles that the storage must deliver	1	<	0.05	15	100000	100000	100000
17	16	Minimum economical life time at normal operating conditions	years	<	0.05	16	20	20	20
18	17	mimimum charging efficiency	%	<	0.05	17	50%	50%	50%
19	18	maximum self discharge	%/hr	>	0.05	18	0.057%	0.057%	0.057%

Fig.3 The "Cases" Spreadsheet

Aside from this ease of use aspect, the Excel application is highly editable and can generate large amounts of analyzed data within seconds. The starting Workbook totalizes three Spreadsheets: the one where application cases are described, the one containing the parameters of the available storage technologies and finally the results spreadsheet.

In the "Cases" Spreadsheet, all the required parameters of the storage system are listed, together with the restrictions imposed by the application. When developing the structure of the table, a similar approach to relational databases has been used, in order to eliminate redundancy and increase computing speed and clarity for the user (Fig. 3).

Although 20 parameters have been used to model the requirements of a particular application, the Spreadsheet is not limited to this number, as additional lines and columns that respect the overall used format are automatically parsed by the software application.

The Spreadsheet "Storage options" contains more than 10 known storage technologies, like: lead–acid, Li-Ion, redox flow, nickel or thermal batteries, supercapacitors, flywheels, pumped hydro, CAES, SMES, fuel cells. Also, the number of parameters taken into account is user defined and totalizes in most application over 15 parameters (Fig. 4).

	A	B	C	D	E
1	PropID	Property name	unit	Lead-acid batteries	Li-Ion batteries
2	1	type of grid connection	dc or ac	0	0
3	2	minimum operating voltage range / commercial unit	V	1.75	2.7
4	3	maximum operating voltage range / commercial	V	0.24	0.58
5	4	minimum time to put store back to SOC_avg (recovery time)	hr	3	2
6	5	nominal cycle time	hr	15	9
7	6	Maximum total response time delay	ms	0	0
8	7	maximum number of full cycles	1	800	3000
9	8	Maximum power vs. time within rated voltage range (diagram)	=	1	1
10	9	minimum operating temperature	degC	-40	-40
11	10	SOC minimum (rated)	%	5	5
12	11	maximum operating temperature	degC	+60	+60
13	12	SOC maximum (rated)	%	100	100
14	13	minimum energy density of a commercial unit	kWh/m^3	35	170
15	14	round cycle efficiency	%	92	90
16	15	maximum number of micro cycles	1		

Fig. 4 The "Storage options" Spreadsheet

The connection between this first two spreadsheets is done like in the case of relational databases, through the ID columns. The "ReqPropId" field in the "Cases" spreadsheet references a line marked by the "PropId" in the "Storage options" spreadsheet. This way an intuitive method is provided to the user.

The final spreadsheet of the software application is used to output and manage the results. The total weight of the unfullfiled requirements is displayed for each (storage system, application) pair. Moreover, the parameters of the storage technology that failed to meet the requirements of a particular application are listed in cell comments as one can see in Fig.5. Although the interface might look simple, it folds complex VBA code, in which al the macros necessary to handle data described by the user have been developed.

V. Conclusions

There are various applications of storage technologies which aim at enhancing the static and dynamic behavior of the active distribution systems. Together with new control algorithms, like the Virtual Synchronous Generator (VSG), implemented into versatile power electronic modules, which interface generating units and the network, the electrical storage can become a powerful tool for improving the electric power transfer while improving the system stability at normal operation and during significant perturbations. In this paper the description of each VSG application case is made such that the algorithm for detecting the best storage technology among the available ones can be further applied to other short-term energy applications. In the final paper, result will be given for selection of the best available storage technologies for VSG's.

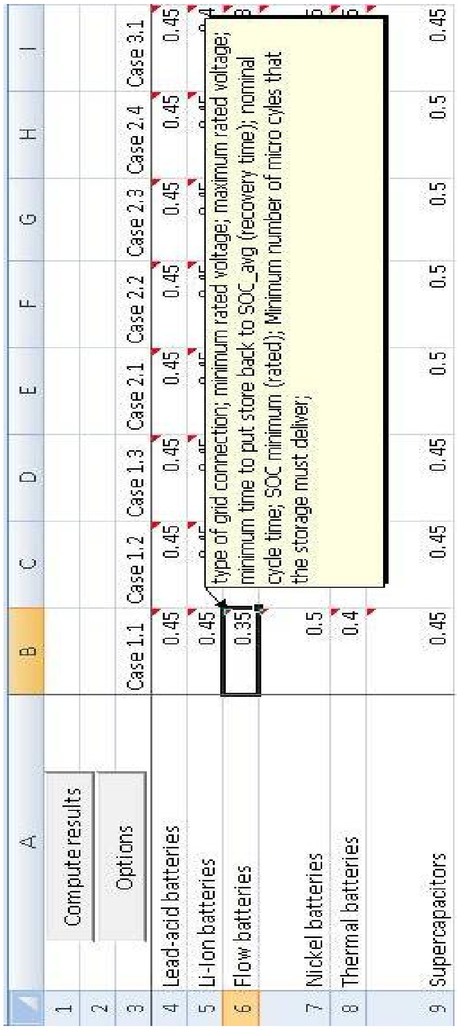

Fig. 5 The “Results” Spreadsheet

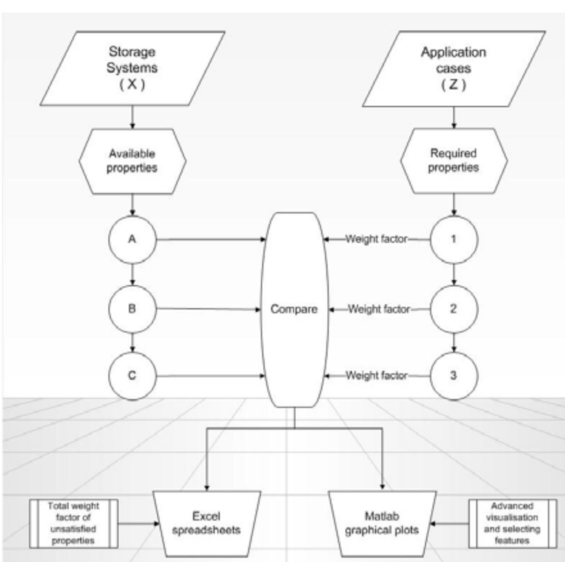

Fig. 6 Concept of the algorithm

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VII. Biographies

Mihaela Albu (M’96–SM’07) is from Craiova, Romania. She graduated from “Politehnica” University of Bucharest in 1987 and holds the Ph.D. degree (1998) from the same university. Since 2002 she is a Professor of Electrical Engineering. Her research interests include active distribution networks, DC grids, power quality, instrumentation, and remote experimentation embedded within on-line laboratories. Dr. Albu was spending a leave at Arizona State University as a Fulbright Fellow 2002 - 2003.

Klaas Visscher received his Master's degree in 1988 and his Doctor's degree in 1993, both in Applied Physics at Twente University in The Netherlands. Next he worked several years on automation projects in his own consultancy. In 1999 he joined the Energy Research Centre of The Netherlands, where he first worked on heat storage and thermal processes for renewable energy applications for three years. In 2003 he joined the Intelligent Energy Grids program of ECN, working in the field of distributed power generation. As research co-ordinator Grid Connection and Power Quality in the ECN Intelligent Energy Grids program, the main topics of his current research are control and stability of distributed electricity generation systems in future grids.

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Alexandru Nechifor is an undergraduate student at Politehnica University of Bucharest. Being part of MicroDERLab group, his main research activities are in the field of remote measurements and control of LV grids.

Nicolae Golovanov is from Braila, Romania. Since 1990 he is Professor at the Department of Power Engineering of the “Politehnica” University of Bucharest. He has published more than 100 papers and 20 books on power system topics. His fields of interest include distribution grids, including measurement and power quality. He is a member of the Power Engineering

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