Flexibility sources for enhancing the resilience of a power grid in presence of severe weather conditions

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***Abstract*—Severe weather events are increasing in frequency and intensity over the time with increasingly severe impacts on daily human activities, often dramatically inhibited by disastrous consequences with disruptions of communications, goods, public transports water and energy services. In this context the electric grids are very vulnerable and suffer very serious consequences, with presence of multiple contingencies. It is therefore necessary to have grids with adequate level of resilience to cope with this event and to ensure adequate service levels.**

For this reason, the authors of the paper, in cooperation with the Italian Transmission Operator, have proposed an advanced methodological approach able to improve the resilience levels of transmission grids in presence of natural disastrous events characterized by low probability and high impacts. The new approach is performed by flexibility tools able to combine the flexibility margins of the networks with those of generations and loads. Moreover, in the paper, new indexes have been defined and applied in case studies for the resilience characterization.

***Index Terms*—Power grid resilience, Grid flexibility, flexibility sources, Resilience metrics, Smart grids**

I. Introduction

The increase in human activities in the last two centuries is undeniably producing a climate change due to the growth of climate-changing emissions deriving, above all, from industrial activities, means of transport and domestic heating. The consequences of this tendency manifest themselves with increasingly frequency of meteorological events characterized by disastrous impacts (non credible contingencies), which can be classified as HILP (*High Impact - Low Probability*) [1]. Examples of such events are high-intensity gusts of wind, which in Europe increasingly take on the appearance of tornadoes, high snowfall and high ice thickness even at low altitudes.

They can happen with catastrophic consequences on t communications, transports, and electrical grids , which are designed to cope with only credible events (credible contingencies) for economic reasons. [2].

To address the consequences deriving from these phenomena, the tendency is to study and implement increasingly resilient systems and infrastructures.

For this reason the concept of Resilience is becoming of strong interest in power systems application, not only, it is the very meaning of Resilience normally applied in various fields of Engineering, Security, Agriculture, etc. which is evolving to be more responsive to the representative needs that characterize electrical systems. What is the resilience of a system? Currently there is not yet a precise definition about it, currently the term should indicate the ability of any system of 'bouncing back' after the occurrence of a disruptive event, returning to the initial state.

More generally, Allenby and Fink [3] defined the resilience as the "*Capacity of a system to maintain its function and structure in the face of internal and external change and to degrade gracefully when it must*", whereas Prezenger defined resilience as the "*measure of a system's ability to adsorb continuous and unpredictable change and still maintain its vital function*" [4].

It is starting from these definitions that this concept is becoming characterized for the electric power systems; in particular, the Technical Committee for the Resilience stated that the grid resilience is "*The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event*" [5], which can be figuratively viewed through the resilience trapezoid associated with an event as described by Panteli in [6].

Therefore, the latter definition describes the resilience as a wide concept, which is more extended than that of reliability, that concerns a wide variety of possible events, which spans from the earthquakes to the terrorist attacks, passing through the cyber-attacks, hurricanes, sandstorms and so on.

Furthermore, resilience covers both the planning of power grids and the corresponding management in real time passing for their recovery from a disruptive event over the time.

For this reason it reasonable consider that the study of the resilience might be split on different time horizons, as the long-term, which is planning-oriented on which is the best grid layout to face with the possible HILP events, and the short term, more focused on the handling of contingencies and customers disconnection/re-connection and elements recovery.

The long-term studies need to consider the hardening of the power grid against the possible HILPs, by using stochastic approaches as done in [7], and after simulating all the possible contingencies management.

If this kind of study is the most complete because consider both long and hypothetical short times it is characterized by huge computational costs, in particular for large grids. Further, it is required the knowledge about the past weather history in

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order to catch what could be the severe weather events to cope with [8].

Moreover, this kind of study will produce effects only in a long time because changes in the grid structure, replacements of substations and installation of new generation central require time.

For this reason, the short-term study plays a crucial role because aims to find strategies ready to be acted for reducing the impact of a severe event. This kind of study works on the actual grid configuration, considering only the available resources, realizing a control action for managing the power grid in presence of multiple contingencies.

In this context, flexibility is the key to adopt an effective strategy to avoid grid blackouts, where the term is referred to the system ability to cope with events that may cause imbalances between supply and demand at different time frames while maintaining the system reliability in a cost-effective manner [9].

In particular, the renewable generation, demand response, topology, shift-transformers, storage represent possible flexibility tools [10], which might play a strategic role in the enhancement of the resilience on the short time, overall in the first phase of the severe event, in which the resilience of the system goes down.

In literature, several works have proposed outage management schemes for the micro and distribution grids in order to limit the load shedding in presence of component faults as proposed in [11] and [12] whereas a correspondent application in the transmission network has been faced with only by the authors [13], where the possible outages have been estimated by considering the grid structure.

In light of this the authors of this paper aims to propose an advanced methodological approach able to reduce the drops of grid resilience levels, avoiding the uncontrolled disconnection of portion of the grid, caused by over current line protection systems, in presence non credible contingencies.

This methodology has been tested on a real case study represented by a 150-kV transmission grid placed in the North-East of Italy, around the area of the Dolomites, where severe weather conditions occurred in the winter of 2013.

In addition, new metrics have been proposed to quantify the enhancement of resilience obtained by the proposed methodology

II. Mathematical Formalization

This paper proposes an advance methodology to enhance the grid resilience based on the employment of flexibility tools, such as the load flexibility, to support the TSO in limiting the cascade effect caused by multiple outages in presence of severe weather conditions, by applying this in a real case study.

This methodology includes an outage management scheme in order to assure the optimal operation of a power grid when it is affected by multiple lines interruption, which are disrupted by tree falls in presence of severe weather conditions. This allows to avoid possible cascade events, such as the action of the over current protection systems, which will reduce the number of available connections over the grids.

In light of this, the flow chart of figure 6, well summarized the operation of the proposed methodology, which has as input data the updated grid topology in case of component faults on the grid, the online measures on load and generation other than further information about generation and load units, where these latter are characterized as an equivalent load for each connected distribution grid to the transmission one of interest.

For this reason, the controllability of the load units corresponds to applies load shedding protocols to the aggregated sub-units load or by using local generation, as storage or backup generator units.

For this reason, the hypothesis of load units equipped by the smart control tools aimed to disconnect or regulated the load supply has been done.

Thus, the objective is mathematically supplying the maximum demand as possible, which as shown in the eqs. 1a - 1h , in presence of a grid faults as permanent damage of transmission lines , for which the bus voltages and the line currents could be out of the operation constraints.

$$\min_{\mathbf{x}^t = [\mathbf{x}_L^t, \mathbf{x}_G^t, \mathbf{v}_x^t]} \quad f(\mathbf{x}) = \sum_{i=1}^{N_L} \Delta {L_i^t}^2 + \sum_{j=1}^{N_G} \Delta {G_j^t}^2 \tag{1a}$$

s.t.

$$\mathbf{0} \leq \mathbf{x}_L \leq \mathbf{P}_L^0, \tag{1b}$$

$$({\mathbf{P}_G^t}^0 - \mathbf{P}_{mG}) \leq \mathbf{x}_G^t \leq (\mathbf{P}_N - \mathbf{P}_G^0), \tag{1c}$$

$$\mathbf{v}_m \leq \mathbf{v}_x^t \leq \mathbf{v}_M, \tag{1d}$$

$$\mathbf{v}_m \leq \mathbf{u}^t \leq \mathbf{v}_M, \tag{1e}$$

$$\mathbf{S}^t \leq \mathbf{S}_{max}, \tag{1f}$$

$$P_{G}{}_{(r)}^t - P_{L}{}_{(r)}^t = V_r^t \sum_{s=1}^{N} V_s^t (G_{rs} cos(\theta_{rs}^t) + B_{rs} sin(\theta_{rs}^t)), \tag{1g}$$

$$Q_{G}{}_{(r)}^t - Q_{L}{}_{(r)}^t = V_r^t \sum_{s=1}^{N} V_s^t (G_{rs} sin(\theta_{rs}^t) - B_{rs} cos(\theta_{rs}^t)) \tag{1h}$$

with:

$$\begin{cases} \mathbf{P}_L^t = \mathbf{P}_L^0 - \mathbf{x}_L^t & (2a) \\ \mathbf{P}_G^t = \mathbf{P}_G^0 + \mathbf{x}_G^t & (2b) \end{cases}$$

and

$$\begin{cases} \Delta L_i^t = P_{L}{}_i^t - P_{Li}^0 = -x_{L}{}_i^t & (3a) \\ \Delta G_j^t = P_{G}{}_j^t - P_{Gj}^0 = x_{G}{}_j^t & (3b) \end{cases}$$

where 1a is the objective function, which can be decomposed in two terms where the first considers the deflection from the generation program for each generation unit and the latter for the units of load.

In particular, the hypothesis of proportional variation between active and reactive power for the load was made by assuming that $cos\phi = cost$

The described terms can be further expanded in the equations 2a and 2b, in which it is possible observing that increments in x_L correspond to load reduction whereas increments in x_G corresponds in increasing the power generation by the power units.

The variations than the scheduling are limited by the constraints 1b, whose bounds regulate the load reduction level, 1c, which regulates the increasing and decreasing of the power production, 1c and 1d, whose bounds allows a voltage amplitude value included between the -10% and $+10\%$ respect to the nominal value for each bus.

Obviously the limits on the transmission line capacity is taken into account with the constraint 1f, whereas further constraints are the power flows equations of 1g and 1h, for which the left members represent the local active and reactive net balance for each considered bus as shown in eq. 3a and 3b.

In particular, the above formalization acquires a strong meaning when coupled to many resilience metrics, which are still in phase of developing for what concern the power grid resilience and where they cans both operative and structural aspects as shown in [6].

In this case the equations 2a and 2b play a crucial role to assess the resilience level of the system, which is here defined as the ratio between the total amount of the load preserved from load shedding and the corresponding quantity requested before the disruptive event, which can be mathematically expressed as:

$$R^t = \frac{{P_L}^t}{{P_{L0}}^t} \in [0, 1] \tag{4}$$

where this is the ratio between the supplied demand after the regulation action to respect the system operation constraints and the demand supplied until the occurrence of the severe event that had provoked the activation of the described procedure of system optimization.

Thus, when the power grid is able to still respect the same amount of demand in presence of one of more components faults the value of the resilience index is equal to 1 whereas, if the grid is able to supply a lesser demand respecting the system operation constraints this index will decrease with a drop of its resilience.

Unfortunately, the latter metric supplies information only about the current capability of the grid to satisfy the demand in presence of multiple faults, showing a lack in supplying information about how fast the resilience change is.

Thus, the introduction of an appropriate metric, which considers the incremental ratio of resilience, might supply relevant information on the effect of the adopted strategies to limit the propagation effect of a severe events on the power grid over the time.

Therefore, the key role of this metric is highlighted by fig. 1, which shows the descending part of Pantheli's trapezoid, where many possible system response to a severe event propagation are shown, allowing to supply interesting considerations about the management of a severe event.

In particular, fig.1 shows the evolution of resilience level over the evolution time, where the vertical yellow lines (colored on-line version of the paper) are the triggers signal related to some component has failed in the electric grid (lines, transformers, generators).

Thus, considering the interruption of at least one transmission line if all the buses remain connected to the grid the resilience index above defined will remain equal to 1 for a while because some lines are going in over-loading.

After a while, if the system is in free evolution, (curve 1), the protection system will interrupt the overloaded lines to protect them from over-currents. This is the effect of the propagation of the severe event on the system, causing a drop of resilience due to isolated buses or disconnection of part of the load.

This cascade will end reaching an equilibrium where either a part of the load will be reduced, or the system will be totally disconnected.

Differently, with the control on the flexibility sources the operation of power grid might be gradually adapted to be adherent to the new system constraints (curves 2 and 3), where the load is curtailed or locally supplied with *Electric Energy Storage* (EES), and the speed for realizing depends on the ramps limit for adapting the generation to load reduction.

Indeed, if the system is slows in applying the requested changes (curve 4) a further failure could cause a further resilience drop, therefore, the area included between the curves 2 and 3 can be considered as the locus of the points for which the chosen strategy is still effective.

For this reason, it reasonable introducing a new index that goes to assess the ratio of resilience drop/gain between each trigger signal over all the period under observation.

The observation starts with the time of the last signal on the system state before the first contingency and the next one after the completely recovery of the system, with $R = 1$. Mathematically, this can be defined as:

$$\frac{\Delta R}{\Delta T} = \frac{R^{t_{i+1}} - R^{t_i}}{t_{i+1} - t_i} \tag{5}$$

where the subscript i in t_i consider the time span in which a variation in grid topology is happened.

At this point, it reasonable looking for a way to fuse the information supplied by the previous indexes to assess the effectiveness of the adopted strategy for the whole period of its application, as done in the eq. 6 by considering the area under the curve computed by using the index in eq. 4:

$$A = \int_{t_1}^{t_2} R(t)dt = \int_0^1 \frac{{P_L}^{t'}}{{P_{L0}}^{t'}} dt' \tag{6}$$

where $t' = \dfrac{t}{t_{end} - t_0}$ is the dimensionless time, in this way, the value of A is included between $[0, 1]$, thus if the response of the system to a severe event is the best as possible, avoiding any load interruption, A is 1.

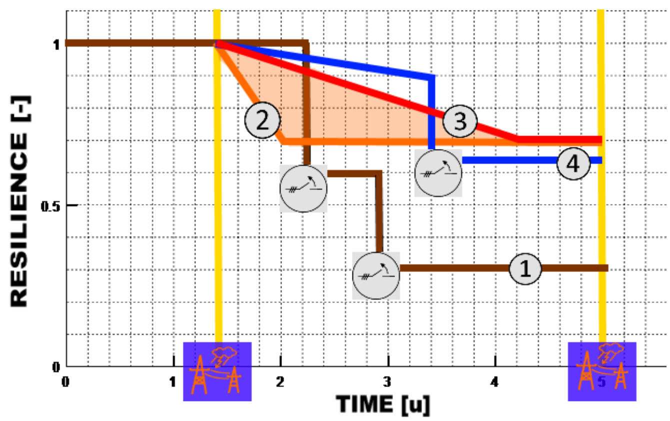

Fig. 1. Evolution of the propagation of a disruptive event

III. Case Study

As described in the previous section this work aims to propose an advance methodology to enhance the resilience of a transmission power grid, in particular by focusing on the event propagation phase, by applying this to a real case study in which any load control was not present.

For this reason, a parallel comparison, by considering the same conditions of that time, was done to quantify the effect of the proposed strategy that, by minimizing the injected power in the load bus from the transmission grid, allows to contain the demand interruption, increasing in this way the level of resilience of the grid.

This has been obtained by applying the mathematical formalization shown in the previous chapter and the corresponding enhancements in resilience metrics have been assessed by using the previous described metrics.

The power grid object of study, whose scheme is shown in fig. 2, is composed by 22 buses, 20 generators units with a total amount of installed power of 370 MVA shared between 11 loads, which represents the aggregated loads for each connected distribution grid, where the total is 357 MVA, as described in table I where the quantities have been expressed in p.u.

IV. Results

This paper proposes an advanced methodology with the objective to guarantee the respect of system operation constraints in presence of severe weather condition.

This has been obtained by adjusting the generation and load programs every time the power grid was affected by a change in its topology, such as due to a line's disruption.

This allows to avoid critical conditions as over-loaded line, which might be opened by the intervention of over-current protection systems, which might lead to wide areas that will be isolated due multiple lines interruption and opening as it was happened in the analyzed case.

TABLE I
Main features of the analyzed power grid

bus	S_L $[-]$	S_G $[-]$	GU	Line	from bus	to bus	$S_{max}[-]$
1	0,01	0,31	2	1	1	2	0,40
2	0,19	0,27	4	2	1	3	0,65
3	0,38	0,00	0	3	2	6	0,76
4	0,25	0,00	0	4	3	6	0,40
5	0,10	0,08	2	5	3	4	0,40
6	0,00	0,21	2	6	4	20	0,40
7	0,26	0,00	0	7	20	5	0,40
8	0,23	0,00	0	8	7	8	0,65
9	0,00	0,25	1	9	8	9	0,40
10	0,22	0,00	0	10	9	22	0,40
11	0,11	0,08	2	11	22	10	0,40
12	0,24	0,00	1	12	11	8	0,40
13	0,00	0,12	1	13	11	12	0,40
14	0,00	0,12	1	14	12	13	0,40
15	0,00	0,00	0	15	12	15	0,40
16	0,00	0,00	0	16	15	21	0,34
17	0,00	0,97	4	17	14	21	0,34
18	0,40	0,00	0	18	21	9	0,34
19	0,00	0,40	1	19	15	17	0,34
20	0,00	0,06	1	20	15	16	0,40
21	0,00	0,00	0	21	16	17	0,36
22	0,00	0,00	0	22	19	15	0,55
				23	18	15	0,40
				24	5	22	0,40

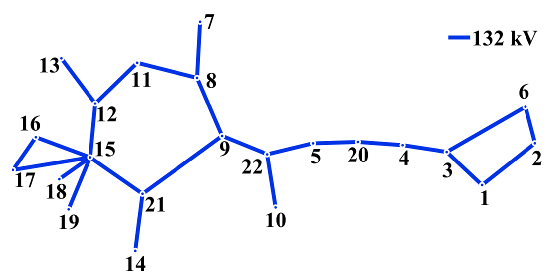

Fig. 2. Graph of the electric power grid at 150 kV object of study

The obtained results have been summarized in tab. II where the percentage of connected load to the transmission grid, the percentage of curtailed load than this latter, the previous defined resilience metrics, have been reported for each change of the grid topology related to a certain disruption.

In particular, by observing the obtained results, a flexible demand would have allowed to still supply more than the 30% of the total demand as shown in fig 3, increasing the resilience index R (eq. 4), avoiding the blackout of the electric grid.

Thus, as above described is further analyzed in fig. 4, in which the ratio of resilience drop is compared in the two cases, where the resilience drop in case 1 is much lower than the case 0 in the first time interval.

Obviously, in the successive two time steps the resilience drops of case 0 is null because the grid was already gone in blackout.

The observed fast severe event propagation is allowed by the particular structure of the analyzed grid, which is not enough meshed yet, as well as the not negligible fact that in the winter period, especially in that portion in which the severe event was occurred, the demand was much greater than the annual average because the considered area is mainly touristic.

For this reason, loss of loads implied much heavy consequences on the local economy that will be transformed in cost to pay for the interruption.

Thus, the challenge is not only minimizing the quantity of load for avoiding the blackout but how it might be possible locally compensate the lack of supply from the transmission grid.

Obviously, this challenge pushes for much cooperation between national TSOs and the several DSOs, whose grids will have to be even smarter. The employment of storage and advanced policies of demand response also in critical conditions are the keystone to cope with this problem whereas a further challenge is involving the local renewable energies, by considering the expected production. In this case the advanced weather forecasting methods will be applied for the application of Dynamic Thermal Rating also, which allows to dynamically increase the transfer of capacity of a transmission line.

At last but not least, for what concern the restoring phase that has not been object of study in this paper, where the challenge is finding the best path to restore the grid in order in the fast time as possible.

For this reason, successive study on the base of the existent literature for this case study the real restore path, which was adopted in TSO at the time, need to be considered.

V. Conclusion

The aim of this paper is that to propose an advanced methodology for increasing the resilience of the grid, with particular reference to the propagation phase of the severe events, based on the possibility to apply flexibility tools to a real case study. The new approach limits the cascade effect of multiple outages on a power grid in presence of severe weather conditions by adjusting, deflecting as less as possible from the market programs, load and generation, by solving an optimization problem.

At the same time, the methodology makes it possible to improve the concept of resilience of the electricity grid. It allows to evaluate the ability for a system to react to a strong disturbance by considering all the phases in which a serious event can be broken down.

In addition, the authors have introduced and discussed new metrics to better quantify this ability by considering several fundamental aspects, which are the assessment of the resilience drop ratio, to quantify the amplitude of the severe event respect to the time, and the efficiency index that allows to quantify the effectiveness of the adopted strategy, by playing a strategic role in making comparisons between different strategies.

The obtained results, for a real severe weather event occurred in December 2013 on the north-east of Italy for a 150 kV electric grid, have highlighted the potentiality to employ demand response policies to limit the disastrous cascade event due to multiple outages on the power grid.

Furthermore, the work has focused on the importance of cooperation between TSO and the several DSO to cope with the problem how realize a electric power grid more resilient, describing the crucial role that will be played by the flexibility sources, which are load, storage and in the not far future the renewable sources, in this challenge, other than to be the core for the next developments in this field for this research group.

Acknowledgment

This research was supported by OSMOSE (Optimal System-Mix Of flexibility Solutions for European electricity) project.

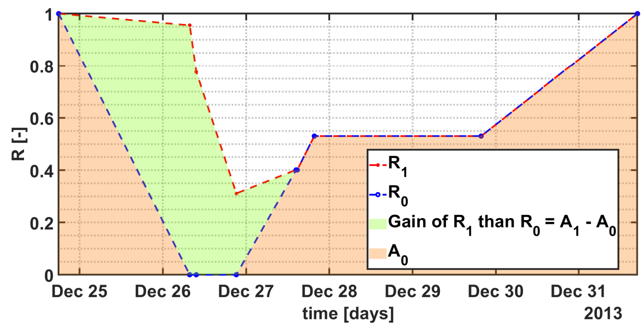

Fig. 3. Experimental Trapezoid obtained by the analyzed event

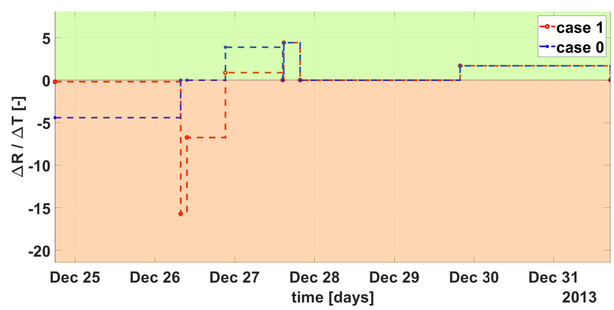

Fig. 4. Ratio between the resilience drop and time for two consecutive grid topology changes, where the quantities have been expressed with dimensionless time

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TABLE II
COMPARISON OF THE RESILIENCE EVOLUTION OF THE GRID IN CASES OF CONTROLLED (1) AND NOT (0) LOAD

	Fault time	Interrupted (*restored*) line	% Connected load	% curtailed load	R^0 [-]	R^1 [-]	A^0 [-]	A^1 [-]	$\frac{\Delta R_0}{\Delta t}\left[\frac{1}{h}\right]$	$\frac{\Delta R_1}{\Delta t}\left[\frac{1}{h}\right]$
1	—				1.0000	1.0000			0.0000	0.0000
2	24/12/2013 07:45	12	100%	5%	0.0000	0.9552	0.1130	0.2210	-0.0265	-0.0012
3	26/12/2013 09:39	9	82%	3%	0.0000	0.7763	0.0000	0.0099	0.0000	-0.0941
4	26/12/2013 21:11	16-18	31%	0%	0.0000	0.3107	0.0000	0.0375	0.0000	-0.0404
5	*27/12/2013 14:24*		*40%*	*0%*	*0.4009*	*0.4009*	*0.0367*	*0.0367*	*0.0233*	*0.0052*
6	*27/12/2013 14:46*		*40%*	*0%*	*0.4009*	*0.4009*	*0.0008*	*0.0008*	*0.0000*	*0.0000*
7	*27/12/2013 19:40*		*53%*	*0%*	*0.5302*	*0.5302*	*0.0137*	*0.0137*	*0.0264*	*0.0264*
8	*29/12/2013 19:45*		*53%*	*0%*	*0.5302*	*0.5302*	*0.1527*	*0.1527*	*0.0000*	*0.0000*
9	*31/12/2013 16:59*		*100%*	*0%*	*1.0000*	*1.0000*	*0.2073*	*0.2073*	*0.0104*	*0.0104*
					Total =	0.5081	0.6795			
					$\frac{A_1}{A_0}$ =	33.70%				

The italic type means the considered phase is that of restoring, which has been excluded by the study in this work.

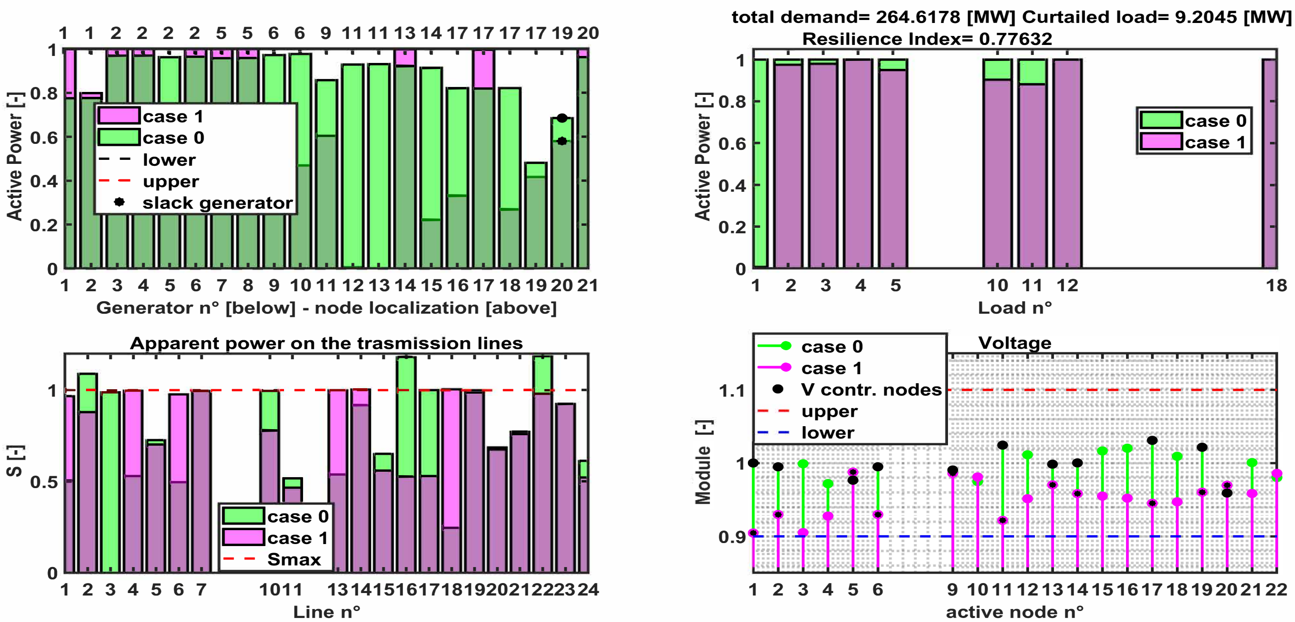

Fig. 5. State of the system after the outage number 3 in controlled and uncontrolled load cases

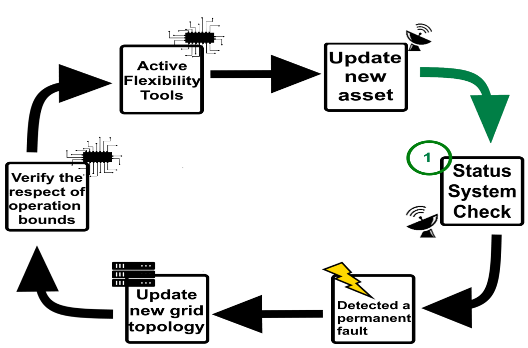

Fig. 6. Flow chart of the proposed advanced methodology

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