Indices to Assess the Integration of Renewable Energy Resources on Transmission Systems

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Abstract-- **The continuous increase on the penetration levels of Renewable Energy Sources (RES) in power systems has led to radical changes on the design, operation and control of the electrical network. This paper investigates the influence of these changes on the operation of a transmission network by developing a set of indices, spanning from power losses to G.H.G emissions reduction. These indices are attempting to quantify any impacts therefore providing a tool for assessing the RES penetration in transmission networks, mainly for isolated systems. These individual indices are assigned an analogous weight and are mingled to provide a single multi-objective index that performs a final evaluation. These indices are used to evaluate the impact of the integration of RES into the classic WSCC 3-machine, 9-bus transmission network.**

Index Terms—**Energy policy, multi-objective assessment, power system planning, renewable energy sources.**

I. Introduction

EUROPEAN Union countries have a set of specific targets to promote the use of energy from *Renewable Energy Source* (RES) in accordance to the Directive 2009/28/EC of the European Parliament [1]. These *National Action Plans* (NAPs) consider and set targets for the final use of energy for heating and cooling, electricity generation and transportation. In particular, electricity generation is of great interest as it requires the liberalization of the electricity markets.

The 16% of global final energy consumption comes from renewable sources during 2012, with 10% coming from traditional biomass, which is mainly used for heating, and 3.4% from hydroelectricity. New renewable sources (small hydro, modern biomass, wind, solar, geothermal, and bio-fuels) accounted for another 2.8% and are growing very rapidly [2]. The share of renewable sources in electricity generation is around 19%, with 16% of global electricity coming from hydroelectricity and 3% from new renewable sources [2].

Nevertheless, RES have not been a significant part of the energy mix for the vast majority of countries around the world, fact which has led governments to provide incentives to entities that are interested in investing in RES electricity generation, in most cases using wind and solar power.

Consequently, it is of crucial importance to investigate how RES generation affects the network's operational ability and which potential configurations could prove beneficial. Hence, a series of technical aspects must be considered by the planners in order to evaluate the pros and cons of such penetration. In particular the minimization of power losses has so far been the most important issue for the planners [3]-[4]. However, other grid related technical aspects have to be considered since they are significant as well. Such aspects are: voltage profile improvement, short-circuit level alteration and maximization of the network's *Available Transfer Capability* (ATC), [5]-[6]. In addition to these, the *greenhouse gas* (GHG) emissions' reduction is increasingly becoming more important as it reflects on the environmental side of the energy problem. Moreover, the system's security is of great significance since access to reliable, cheap electricity relates to the quality of life of a society. Table I shows a brief summary of the relevant existing literature regarding indices used to evaluate the integration of RES.

TABLE I
INDEX-RELEVANT LITERATURE REFERENCES

Reference	*Power Losses*	*Voltage*	*ATC*	*SCL*	*Emission Reduction*	*Spinning Reserve*
[3]	Yes	No	No	No	No	No
[4]	Yes	Yes	No	No	No	No
[5]	Yes	Yes	Yes	Yes	No	No
[6]	No	Yes	No	Yes	No	No
Present work	Yes	Yes	Yes	No*	Yes	Yes

*: Due to software limitations

There are several aspects to be considered in order to integrate RES into traditional networks. However, there are two parameters that have high impact on the integration of RES plants in the network: the selection of the size (rated capacity) and the installation's location of such plants. This paper investigates these effects by developing a series of indices, spanning from power losses to GHG emissions' reduction, which quantify this impact and provide a tool for assessing the RES penetration in transmission networks, mainly for isolated systems.

The paper is organized as follows; Section II introduces the indices that are used and they are being thoroughly described. Section III presents the test network that is used in this paper together with the results obtained for each index evaluated. Finally, in Section IV a multi-objective assessment is carried out to investigate the overall impact of RES generation on the system's performance.

II. Description of Assessment Indices

In this section the assessment indices are presented. Six individual indices are considered in this paper to evaluate the steady-state performance of the network, each one relating to a specific technical aspect. Table II tabulates the indices' description and acronyms.

TABLE II

INDICES' ACRONYMS

Index Acronym	*Acronym meaning*
ILp	Active Power Losses Index
ILq	Reactive Power Losses Index
IVD	Voltage Profile Index
IC	Available Transfer Capability Index
IEm	Emissions' reduction Index
ISR	Spinning Reserve Index

In particular, *ILp* and *ILq* relate to power losses, active and reactive respectively. *IVD* is used to define the voltage deviation. *IC* is related to the system's available transfer capability, *IEm* relates to the GHG emissions reduction and *ISR* to the spinning reserve of the system, meaning the total synchronized capacity, minus the losses and the load [7]. All these indices are explained in the next subsections. For clarification purposes the term *configuration* relates to the scenario under study while the term *base scenario* relates to the scenario without any RES penetration.

A. Power Losses related Indices ILp and ILq

The following indices are used to evaluate the changes on the total active and reactive power losses:

$$ILp^k = 1 - \frac{\mathrm{Re}\{Losses^k\}}{\mathrm{Re}\{Losses^0\}} \tag{1}$$

$$ILq^k = 1 - \frac{\mathrm{abs}(\mathrm{Im}\{Losses^k\})}{\mathrm{abs}(\mathrm{Im}\{Losses^0\})} \tag{2}$$

where $Losses^k$ refers to the total power losses of the k^{th} configuration of the network whereas $Losses^0$ refers to the total power losses of the base scenario (scenario without RES generation).

Near unity values of these indices imply a maximization of the positive effect of RES integration on losses.

B. Voltage related Index IVD

Voltage issues are of critical significance as they are an indicator of the network's condition. The following index evaluates the maximum voltage deviation of the configuration under study:

$$IVD^k = 1 - (V^k_{\max} - V^k_{\min}) \tag{3}$$

where $V^k_{\max}$ refers to the maximum bus voltage level while $V^k_{\min}$ refers to the minimum bus voltage level of the network for the k^{th} configuration. Near unity values of the index mean small deviation of voltage levels.

C. Available Transfer Capability Index IC

One important aspect of RES integration is the altered branch power flows, meaning the different power flow allocation through the lines of the network. A key parameter to optimally introduce RES plants in a network is the relief in the network's line flows. In other words, the introduction of RES in the network should help in reducing the transmission line exploitation and lead to greater tolerance in demand growth.

The *IC* index is used to evaluate how the configuration under study affects the total branch flows of the network:

$$IC^k = \frac{Scap^k}{Scap^0} \tag{4}$$

where $Scap^k$ refers to the remaining available transfer capability for the k^{th} configuration while $Scap^0$ refers to the remaining available transfer capability for the base scenario. Values greater than unity reflect a positive influence on the *ATC* while values less than unity reflect a negative influence.

D. Emissions' reduction related Index IEm

CO_2 emission production is maybe the most important environmental factor that RES integration has to tackle. This is to be achieved through minimization of the use of conventional, fossil-fuelled plants. Although at first sight it seems that the larger the RES penetration, the less the need for conventional plant use, this is only partially true. Maybe a better statement would be the more reliable RES generation becomes, then there will be a less need for using conventional power plant (CO_2 emitting)

Hence, the following index was developed in order to appropriately calculate the CO_2 emissions' reduction for every possible network configuration. The planner can include this information when assessing the system before reaching to a decision. Near unity index values represent nullification of the emissions produced:

$$IEm^k = 1 - \frac{Emissions^k}{Emissions^0} \tag{5}$$

where $Emissions^k$ refers to the emissions produced for the k^{th} configuration while $Emissions^0$ refers to the emissions produced for the base scenario.

E. Spinning Reserve related Index ISR

Large RES integration radically alters the system's reserve requirements, both short-term and long-term [8]-[9]. The following index is useful for observing the system's operating spinning reserve status for every configuration under study, meaning the total synchronized capacity, minus the losses and the load [7]:

$$ISR^k = \frac{SpinRes^k}{SpinRes^0} \tag{6}$$

where $SpinRes^k$ refers to the spinning reserve of the k^{th} configuration while $SpinRes^0$ refers to the spinning reserve of the base scenario. Over unity values in this index suggest that the available on-line capacity is larger compared to the base scenario whereas less than unity values imply the opposite. This helps the planner to quickly assess the system's ability to supply the demand thus providing an estimate of its security of supply.

F. Auxiliary indices

Three auxiliary indices are introduced in this subsection. These indices are not a part of the evaluation process but they are very helpful for observing the system's status.

The first and most commonly used of these is the *Load Level Penetration index* (*LLP*) [3]:

$$LLP = \frac{P_{res}}{P_{demand}} \tag{7}$$

where P_{res} refers to the RES rated capacity while P_{demand} refers to the active power demand of the system. This index is essentially the percentage of the demand that is supplied by RES plants.

Furthermore the other two indices developed are similar to each other and regard the RES rated capacity in relation to the system's capacity.

These two indices are the ratio of the RES rated capacity over the capacity that existed *before* the addition of RES (*PEC*) and the capacity that exists *after* the addition of RES (*NEC*), i.e. without and with taking into account the RES rated capacity to the previously existing capacity. In (8) and (9) the two indices are expressed in mathematical forms:

$$PEC = \frac{P_{res}}{P_{existing}} \tag{8}$$

$$NEC = \frac{P_{res}}{P_{existing} + P_{res}^{rated}} \tag{9}$$

III. Test Case: Assessment of RES Integration

A. Test Network

The assessment indices presented in the previous section of this paper are used on a classical test network; WSCC 9-bus system which is depicted on Fig 1. The network's data is properly adjusted to suit the objectives of this work (see Table III and IV) and the generators data used in this test system are shown in Table V.

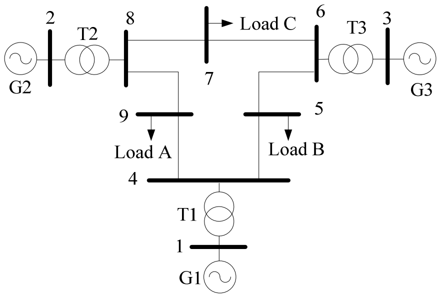

Fig. 1. One-line diagram of the test network: WSCC 3-machine, 9-bus system [13].

TABLE III
BUS DATA

Bus	*Type*	*Pdemand (MW)*	*Qdemand (MVAr)*
5	PQ	90	30
7	PQ	100	35
9	PQ	125	50
Total		315	115

It should be noted that the minimum active power generation is set to 30% of the maximum generation of every generator in order for the system to be more realistic. The fuel type and efficiency selected for each generator are generic but realistic. Furthermore, the reader can find the analytical methodology of emissions production calculation that was utilized for this work in [10].

TABLE IV
BRANCH DATA

From Bus	*To Bus*	*R (pu)*	*X (pu)*	*B (pu)*	*Rated Ampacity (MVA)*
1	4	0.000	0.0576	0.000	250
4	5	0.017	0.092	0.158	250
5	6	0.039	0.170	0.358	150
3	6	0.000	0.0586	0.000	300
6	7	0.0119	0.1008	0.209	150
7	8	0.0085	0.072	0.149	250
8	2	0.000	0.0625	0.000	250
8	9	0.032	0.161	0.306	250
9	4	0.010	0.085	0.176	250

Note: Reactance values are in pu on a 100-MVA base.

TABLE V
GENERATOR DATA

Bus	*P_{max} (MW)*	*P_{min} (MW)*	*Q_{max} (MVAr)*	*Q_{min} (MVAr)*	*Fuel type*	*Efficiency [pu]*
1	250	75	300	-300	Diesel	0.4
2	300	90	300	-300	Coal	0.34
3	270	81	300	-300	Lignite	0.38

A special MATLAB® code was developed to obtain the solution of the optimal power flow problem using routines provided by MATPOWER [11]. In this paper, indices related to short circuit level are not included. It is well-known that the integration of RES may increase short circuit level; however, since there is no available equipment data for the network under study, it is assumed that no rating violation occurs at any scenario. In future endeavors this index could also be added by modifying MATPOWER or by utilizing a different power system simulator.

The MATPOWER data file has been edited in order to assign plant type and efficiency values to each generator. The algorithm caters for several other fuel types.

B. Results and Analysis

In this subsection the results for each individual index of the previous section are presented. The MATLAB® script that was developed executes a series of simulation scenarios. For this particular test network, the scenarios investigated are for 10 MW up to 150 MW of RES rated capacity (i.e. from *LLP = 3.17%* to *LLP = 47.62%*) with a 10 MW step. Every RES rated capacity scenario is examined for every potential installation bus. It should be mentioned that RES plants are considered to operate at a constant power factor *pf=1.0.*

1) Power Losses: ILp and ILq

The results obtained regarding the power losses of every configuration are presented in Fig. 2 and Fig.3, where *ILp* and *ILq* are plotted for several cases. As can be seen, bus 9 presents the most encouraging results as in all cases the active power losses are reduced.

Another interesting aspect of the results obtained is the behavior of the network when a generator shut-down takes place. This occurs at the 70 MW (*LLP*=22.2%) scenarios. The results acquired reflect radical changes in the *ILp* value for almost every bus of the system (see Fig. 2). The changes can be either positive or negative, depending on the new topology of the system (power injections' buses, flow path from generation to demand, etc.). The same effect appears for *ILq* (see Fig. 3) as well. However, it is rather limited in comparison to *ILp*.

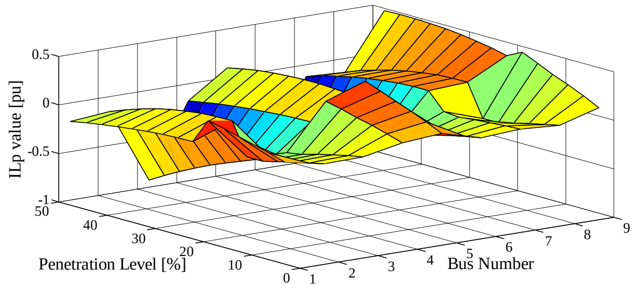

Fig. 2. Active Power losses (*ILp*) versus Location of RES Power Plant and Load Level Penetration.

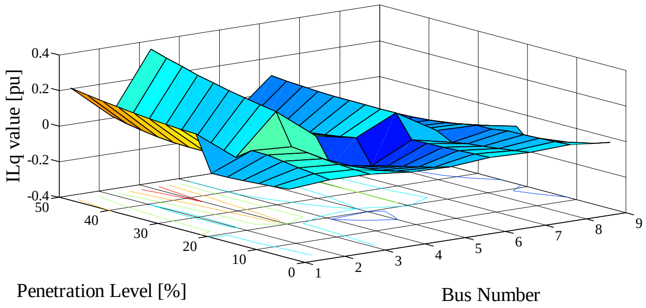

Fig. 3. Reactive Power Losses *(ILq)* versus Location of RES Power Plant and Load Level Penetration.

2) Voltage profile: IVD

Fig. 4 shows the results obtained for the voltage related index, *IVD*. As can be seen, the maximum *IVD* value is 0.9885 and is presented for bus 9. All buses provide an acceptable voltage profile since optimal power flow caters for voltage improvement. However, it is important for the planner to know which configurations lead to smaller voltage deviations as this could lead to less reactive power support investments. The acceptable regulation voltage is assumed 1.00±0.05p.u, thus leaving a 0.1p.u margin for acceptable voltage deviation.

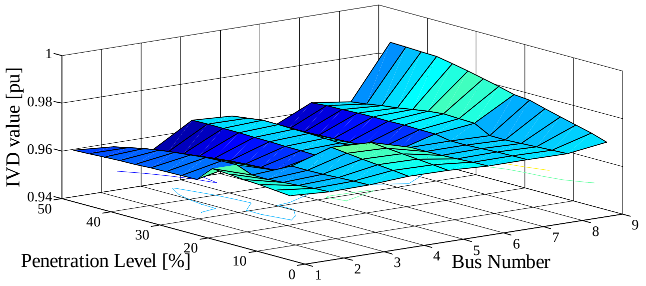

Fig. 4. Voltage profile *(IVD)* versus Location of RES Power Plant and Load Level Penetration.

3) Available Transfer Capability Index: IC

IC index is a way to measure the potential benefit of RES penetration in terms of branch power flow alteration. If a configuration leads to a relief of the power flows through the network's transmission lines, then the network becomes more tolerant to load growth. As can be seen in Fig. 5, most configurations present a positive effect on *ATC*. Especially, when RES generation is located at load buses or close to load buses, then the benefit tends to be greater. This, of course, is subject to the network's topology (existing generators, transmission lines, etc.) that define the power flows. For this particular network, the most beneficial bus for RES installation in terms of *ATC* is bus 9. Also, buses 5, 7 and 8 are of similar benefit.

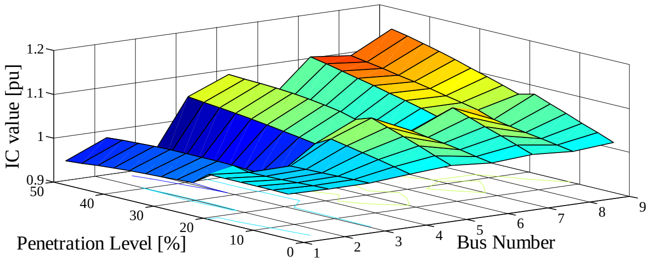

Fig. 5. Available Transfer Capability *(IC)* versus Location of RES Power Plant and Load Level Penetration.

4) Emissions reduction Index: IEm

As can be seen in Fig. 6, the emissions reduction index *IEm* is increasing linearly as RES generation gets larger. This is logical since RES is substituting conventional generation, thus leading to less emission production.

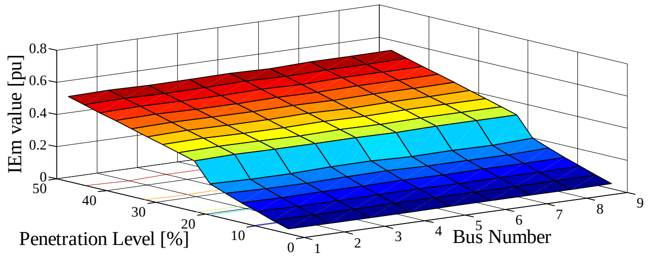

Fig. 6. Emissions' reduction *(IEm)* versus Location of RES Power Plant and Load Level Penetration.

5) Spinning Reserve Index: ISR

In Fig. 7 the results for the *ISR* index are shown. It should be noted that the *ISR* index has a lot in common with the *IEm* index. In a way, they act as complementary to each other. This is due to the fact that when a conventional generator is de-committed and substituted by a RES plant, the security of the system decreases whereas emissions are reduced. It is logical that the security of the system increases as RES generation increases since more generation becomes available. However, when RES generation becomes so large that leads to a de-commitment of a conventional plant, then a rapid decrease of the synchronized on-line capacity takes place. Consequently, this leads to a decrease of the security of the system. This is reflected in Fig. 7 for the 70 MW (*LLP=22.22%*) scenarios.

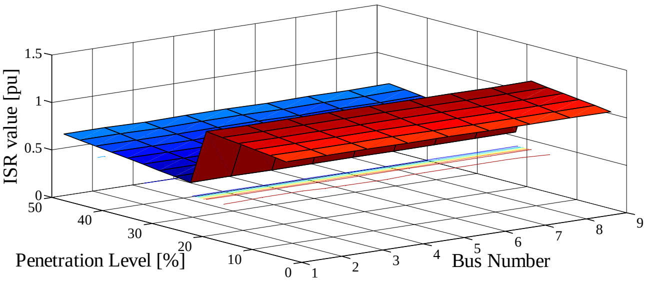

Fig. 7. Spinning Reserve *(ISR)* versus Location of RES Power Plant and Load Level Penetration.

IV. MULTI-OBJECTIVE ASSESSMENT

In order to create a general index that allows evaluating the performance of the network considering all the previously defined indices (except from the auxiliary), a new approach is presented in this paper combining the aforementioned indices into a single *multi-objective index* (IMO).

This multi-objective index is defined as:

$$IMO^k = \sum_{i=1}^{n} w_i \Psi_i^{(k,0)} \tag{7}$$

where w_i is the weight for the ith index while $\Psi_i^{(k,0)}$ is the absolute change of the i^{th} index between the case base (0) and the k^{th} case. In this paper, six indices are considered (n = 6):

$$\Psi_1^{(k,0)} = (ILp^k - ILp^0) \tag{7.1}$$

$$\Psi_2^{(k,0)} = (ILq^k - ILq^0) \tag{7.2}$$

$$\Psi_3^{(k,0)} = (IVD^k - IVD^0) \tag{7.3}$$

$$\Psi_4^{(k,0)} = (IC^k - IC^0) \tag{7.4}$$

$$\Psi_5^{(k,0)} = (IEm^k - IEm^0) \tag{7.5}$$

$$\Psi_6^{(k,0)} = (ISR^k - ISR^0) \tag{7.6}$$

It is important that all weights are normalized and their sum equals one. This is done by dividing each absolute weight value of every index with the sum of all the indices' absolute weight values.

$$\sum_{i=1}^{6} w_i = 1$$

The weight value reflects the importance of each index and is subject to the planner's interests. However, an unbiased evaluation, i.e. all indices given the same weight, could lead to erroneous results as the key factors of the system are given the same significance level as others of less importance.

Although the weight selection is decisive for shaping the results of the evaluation, literature is not very clear on how to define the proper values to each index. It is common, though, that the appreciation of every factor is left on the planner's judgment and personal experience [5]; if the planner cares more about power losses than voltage deviation, then the weights are adjusted accordingly. If on the other hand, considers branch capacity or emissions reduction more important during the planning procedure, then the weights given to these parameters would be increased.

A. Discussion about the Indices' Weight selection

It is apparent that the results of the multi-objective assessment employed in this work strongly depend on the weight selection for each individual index. The weight values are of course defined by the planner in respect to his objectives. Consequently, every planner could potentially reach to a different decision with regard to their subjective judgement.

As a first general approach to the weight selection, power losses indices, namely *ILp* and *ILq*, are considered the most important factors and, therefore, are given the largest weight values summing up to 45% of the total weight value. Specifically, *ILp*, which relates to active power losses, has been so far considered the most important factor as it expresses the direct cost of losses that utilities tend to try and minimize. *ILq* has also received a significant weight value as reactive power support, an ancillary service, is becoming increasingly important to TSOs, as described in [12]. Voltage index *IVD* and *ATC* index *IC* have been given a 20% weight each; that is to show how significant to the network's performance are both voltage improvement and *Available Transfer Capability* as they play an important role in the network's operational profile. Lastly, the emissions index *IEm* together with the spinning reserve index *ISR* are given a smaller but essential percentage, summing up to 15%. The individual weight values are given in Table VI.

TABLE VI
INDICES' WEIGHT SELECTION

Index weight	*Absolute value*	*Normalized value*
w_1	30	0.30
w_2	15	0.15
w_3	20	0.20
w_4	20	0.20
w_5	8	0.08
w_6	7	0.07
Total	100	1.00

Utilizing the weight values of Table VI, the multi-objective evaluation of the configurations presents the results that appear in Fig. 8.

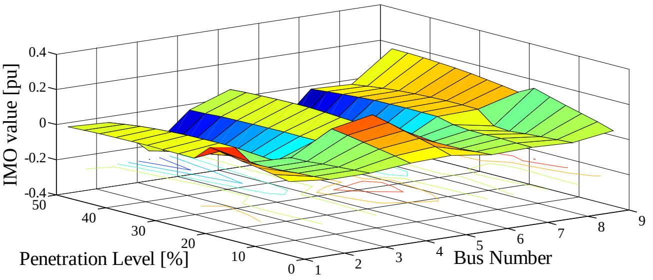

Fig. 8. Multi-objective assessment *(IMO)* versus Location of RES Power Plant and Load Level Penetration utilizing the weight values of Table V.

It comes as no surprise that the best results attained are for bus 9 since it presented the best performance for almost every individual index. It is also the bus with the largest load of the network, which means that the RES generation immediately supplies it, minimizing the need for distant generators to cover the demand. It has to be noted that for bus 9 the *IMO* index values are relatively close to each other, which leaves the planner with a variety of possible configurations that could prove beneficial for the network's planning process. Bus 5 is proven as the second best in performance, fact which also widens the variety of the planner's choices.

Bus 5 is a load bus as well. This suggests that RES integration is usually more beneficial when located at load buses or buses close to the load. The best case is proven to be the 150 MW (*LLP=47.62%)* at bus 9 scenario (presenting an *IMO* value equal to *0.1677).* However, since the indices' weights have been selected as a set of default values, it is of interest to investigate which combination of these weights provides the maximum *IMO* value for the best scenario case.

In order to investigate this, the *Monte Carlo simulation method* is utilized. In a Monte Carlo simulation, a random value is selected for each of the tasks, based on the range of estimates. The model is calculated based on this random value. The result of the model is recorded, and the process is repeated. A typical Monte Carlo simulation calculates the model hundreds or thousands of times, each time using different randomly-selected values. In particular, for each of the iterations, the absolute weight values of the indices are assigned a random number between a lower and an upper limit, defined by the user, thus exploring a sufficient number of possible combinations. The lower and upper limits for each index are shown in Table VII. These limits have been set accordingly in order for their expected values to match the previous default setting (see Table VI) so the comparison can be essential.

TABLE VII
INDICES' WEIGHT LIMITS FOR THE MONTE CARLO SIMULATION

Index weight	*Lower Limit*	*Upper Limit*	*Expected Value*
w_1	20	40	30
w_2	10	20	15
w_3	10	30	20
w_4	10	30	20
w_5	5	11	8
w_6	5	9	7
Total	60	140	100

In Fig. 9 the *IMO* values for the Monte Carlo simulation are shown. The number of samples was set to 200.000 in order for the method to converge. In Fig. 9, the *IMO* values revolve around an average value of 0.1675. This is logical since the expected value of each index weight is the same as in Table V which presented an *IMO* value of 0.1677 (a simulation error less than 0.12%). The maximum *IMO* value obtained from the Monte Carlo simulation is 0.2545 whereas the minimum *IMO* value is 0.09. This is achieved for the weight selections that are presented in Table VIII and Table IX respectively. These results point out the importance of the weight selection for each index which can cause a wide oscillation of the multi-objective evaluation outcome that could lead planners to overestimating or underestimating potential configurations of the system. It also proves the dynamic nature of the problem and clarifies the need for careful consideration before reaching to a decision.

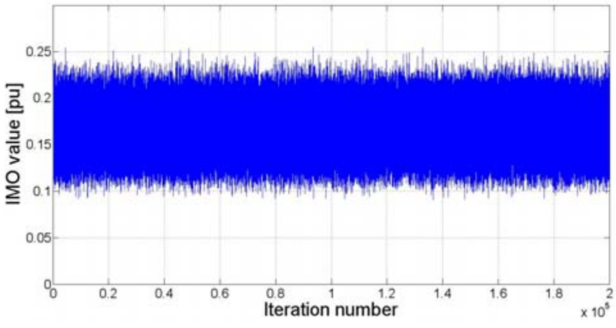

Fig. 9. IMO values for the best case scenario of the Monte Carlo simulation.

TABLE VIII
MONTE CARLO INDICES' WEIGHTS FOR MAXIMUM IMO VALUE

Index weight	*Absolute value*	*Normalized value*
w_1	39.31	0.4550
w_2	10.80	0.1251
w_3	10.88	0.1259
w_4	10.01	0.1159
w_5	10.03	0.1161
w_6	5.36	0.0620
Total	86.40	1

TABLE IX
MONTE CARLO INDICES' WEIGHTS FOR MINIMUM IMO VALUE

Index weight	*Absolute value*	*Normalized value*
w_1	20.37	0.2258
w_2	19.03	0.2110
w_3	26.58	0.2947
w_4	10.53	0.1168
w_5	5.24	0.0581
w_6	8.45	0.0936
Total	90.20	1

V. CONCLUSION

A number of indices that assess the impact, positive or negative, of RES integration were introduced in this paper. These indices cover a wide spectrum of technical aspects that are crucial to the network's operational procedure, spanning from power losses to emissions' reduction and system security. Thus, an attempt to connect the operational stage with the planning process of a power system has been made. These individual indices are assigned a specific weight and are incorporated into a single multi-objective index that caters for the final evaluation of each configuration under study. The weight selection is proven to be crucial to the final outcome of the evaluation. This was investigated through a Monte Carlo simulation that pointed out the potential *IMO* variation of the same network configuration when the weight selection varies between certain limits. Therefore, this work pins out the need for careful consideration of every factor when planning with RES, especially for isolated systems that exacerbate possible contingency situations since there can be no external support from other inter-connected networks that can act as a source or sink of energy. In conclusion, this work examines the impact of RES integration in the system's operational stage in order to determine the technical constraints that directly or indirectly affect the system planning process and, consequently, define the parameters for shaping the National Action Plans of each country.

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