Stochastic Assessment of Investment Efficiency in a Power System

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Abstract

The assessment of investment efficiency plays a critical role in investment prioritization in the context of electrical network expansion planning. Hence, this paper proposes new criteria for the cost-efficiency investment applied in the investment ranking process in electrical network planning, based on the assessment of the new investment candidates impact on active-power losses, bus voltages and line loadings in the network. These three general criteria are chosen due to their strong economic influence when the active-power losses and line loadings are considered and due to their significant impact on quality of supply allowed for the voltage profile. Electrical network reliability of supply is not addressed, since, this criterion has already been extensively applied in other solutions regarding investment efficiency assessment. The proposed ranking procedure involves a stochastic approach applying the Monte Carlo method in the scenario preparation. The number of scenarios is further reduced by the K-MEANS procedure in order to speed up the investment efficiency assessment. The proposed ranking procedure is tested using the standard New England test system. The results show that based on the newly involved investment assessment criteria indices, system operators will obtain a prioritized list of investments that will prevent excessive and economically wasteful spending.

Keywords

Assessment of investment efficiency, investment criteria, active-power losses, line loadings, voltage profile, stochastic scenarios.

1. INTRODUCTION

Assessment of the investment efficiency in a power system can be a complex and thought-provoking issue for the system operators (SO), that merits a closer look. Some SOs apply simple and traditional assessment procedures (contingency analysis, power-flows, etc.) in including the new investment candidates in the electrical network, whereas others SOs oppose these simple procedures and support probabilistic approaches for cost-efficient investment and improved SOs performance in a performance-based regulation (SOs perceive awards, thus, profitable gains). This latter position is certainly the stronger of the two, as a consequence of the random nature of the electrical network components and should be examined in detail.

Up until now, the literature has recognized a variety of electrical network planning methods. Investment assessment is vital component of the electrical network planning, since it helps the SOs to easy-decide the expansion or reinforcement investment. In [1], a traditional electrical network expansion planning procedure is presented, elaborating the impact assessment, power system operation simulation and financial analysis as the main ground steps in an integrated energy utility's traditional planning practice. Also, a comparison is made underlining the substantial differences between electrical network expansion planning procedures in two regulation environments. It is ascertained that the reliability assessment is gaining points in the assessment of investment efficiency. In [2], it is pointed out that deregulation of the power system has introduced new objectives and requirements for the electrical network expansion planning problem. Authors have used a multi-objective optimization framework as static electrical network expansion planning methodology. Three terms are included in the objective function: investment cost, reliability and congestion cost. To obtain the final optimal expansion decision fuzzy decision making is applied. In [3], reinforcement and expansion of the electrical network is proposed as a way to mitigate the impact of increasingly plausible deliberate outages. The network planner selects the new lines to be built accounting not only for economic issues, as traditionally done, but also for the vulnerability of the transmission network against a set of credible intentional outages. The resulting vulnerability- and economic-constrained electrical network expansion planning problem is formulated as mixed-integer linear program. In the paper, the objective function comprises two terms. The first term represents the vulnerability of the transmission network against intentional attacks and the second term accounts for the investment cost by employing a binary variable. The complex mathematical formulation is formulated as mixed-integer linear programming problem. Furthermore, deregulation of the electric power industry has employed new uncertainties for the electricity market participants and has made the electrical network planning more difficult. In [4], a novel electrical network expansion planning approach is proposed to meet the electricity market uncertainties by employing a statistical approach and identifying several possible future scenarios. In the proposed approach, the electrical network expansion planning is formulated as mixed integer nonlinear programming problem, including the expected energy not supplied and the adoption cost of the electrical network expansion plan. In [5], a mixed-integer linear programming formulation for the long-term electrical network expansion planning problem in a competitive pool-based electricity market is presented. In the paper, market functioning is modeled while defining a number of scenarios based on the future demand of the power system. Also, the investment and operating costs, transmission losses, generator losses and demand bids are considered in the optimization procedure. Another part of the electrical network expansion planning process is the retirement decision making. In [6], the simultaneous generation expansion and retirement planning problem is formulated as an optimization problem. It includes the retirement decision of aged generating units in the expansion process, which might be beneficial, since old units can work with increased costs and decreased efficiencies. The objective function is set to minimize the expected total cost consisting of the investment required for the commissioning new units, operation and maintenance costs, retirement salvage costs and system risk costs. The objective is subjected by the generating unit and the system physical and operational constraints. In [7], a new approach has been developed, based on the probabilistic failure density of the electrical system components, for the life assessment of the electrical components and decision-making support. What criteria should guide electrical network expansion planning is a crucial issue, since the least-cost expansion planning is no longer viable. In [8], a new framework is presented for multi-objective electrical network expansion planning. It is based on a multiple criteria decision making whose fundamental elements are network reliability and electricity market. In [9], a new method is introduced for choosing the best electrical network expansion plan considering a probabilistic reliability criterion based on the uncertainties of transmission system elements. In [10], a multi-criteria formulation for multiyear dynamic transmission expansion planning problems is presented. The investment and operation costs and the energy not supplied are considered in the establishment of the decision criteria. Still, as stressed in [11], there is an enhancement necessity to improve the traditional electrical network expansion planning by applying probabilistic approaches. Therefore, to the traditional single contingency security criteria N-1, multicomponent outages must be considered, since the random nature of the power system components have a great effect on power system performance. The occurrence probability of outages must be simulated, uncertainties in network topologies, probabilistic power-flows and stability assessments. Other reasons to include probabilistic approaches in the electrical network expansion planning can be found in [12] and [13].

Above all, the existing planning procedures have been recently upgraded with an assessment of investment efficiency for prioritization and easier decision making. In [14], a method is presented for ranking and postponing investments in the electrical network planning part. A probabilistic economic criterion which takes into consideration the cost of expected undelivered energy is used to derive a profitability index, a postponement index and combined technical-economical-probabilistic planning criteria to allow the ranking and postponement of technical justified but economically unjustified investments. This ranking method is especially useful when insufficient investment funds are available for construction. In [15], another ranking methodology for the investments in electric distribution grid is presented. As noted, this ranking criteria was involved to harmonize the quality of service criteria required by the regulatory authorities. In the paper, the presented ranking methodology seeks to identify the group of projects, which presents the highest return on a given amount of available capital. The ranking is performed based on the technical and economic performance of the planned investment. In [16], a new method for reliability investment decisions when a reward/penalty scheme is applied to the regulation of SOs is presented. New investment planning criterion for SOs subjected to performance based regulation (PBR) is identified and mathematically formulated as new investment efficiency index (IEI), which yields the relation between the improvement of system reliability due to the investment in the electric system and total investment costs. To determine the improvement of system reliability due to the investment in the electric network, the method uses the Monte Carlo simulation technique for the modeling of the stochastic nature of outages in electric networks, along with a linear program, which enables load flow calculation under a fault state that provides information about power deficits in the electric system.

For this paper, the core research has already been approved and shown in [16], however, in this paper the research developed in [16] is improved by elaborating a ranking procedure of proposed investment candidates based on their operational effect and investment cost, similar to the reliability investment decision method presented in [16]. The investment cost includes calculation of the actualized investment cost and the operational effect includes examination of the proposed investment candidate effect on active-power losses, voltage profile and lines loadings. The ranking procedure is developed to enhance the transition from cost-based to performance-based regulation by employing new cost-efficient investment planning ranking criteria. Finally, this paper makes six contributions, noted as following:

- New cost-efficiency investment index named *LEI*, which yields the relation between the decrease of the active-power losses due to the investment in the electrical network and total investment costs. The active-power losses are accounted, since investment candidates that reduce the active-power losses in the power network lead to reduced costs for purchasing ancillary services for compensating the active-power losses, since these costs have to be covered by the SOs and charged to end-users,
- New cost-efficiency investment index named *VEI*, which yields the relation between the improvement of the voltage profile due to the investment in the electrical network and total investment costs. Bus voltages have a significant impact on the voltage profile of the power network, i.e. on quality of supply, which must be constantly improved or at least maintained at acceptable levels as defined by regulations; otherwise, final consumers may demand restitution, which is additional cost for the SOs,
- New cost-efficiency investment index named *PEI*, which yields the relation between the line loadings mitigation due to the investment in the electrical power network and total investment costs. Lines overloading may cause shortage of transmission capacity. Selection of investment candidates that will not additionally burden the electrical power network and that would increase the reliability of the power network must be enforced by engaging new methods for cost-efficient investment,
- Stochastic scenario modeling in the expansion planning process to comprise random nature occurrences using probabilistic approach. In this paper, the stochastic scenario modeling comprises the availability of the power lines and loads variation. The availability of power lines is considered, since renewables can be integrated in the power system at different points and cause outages as a consequence of overloading. Loads variation is stochastically modeled as a consequence of the final consumer needs and behavior. Additionally, the traditional electrical expansion planning must be enriched by engaging stochastic approaches. In this paper, we have employed the Monte-Carlo procedure to derive probabilities of operating states and include the occurrence weights in the assessment task,
- Cost-efficiency stochastic assessment of the full deployment of investments identified towards the achievement of the envisaged strategic targets. The need for more investment in power network must be acknowledged so that the achievements of the ascertained (national) targets are envisaged,
- Applicability of the new, stochastic investment efficiency indices, regarding the active-power losses, voltage profile improvement and lines loading mitigation, *LEI*, *VEI* and *PEI*, respectively, as constraints in the traditional optimization power network expansion planning models, as for e.g. presented in [3]. The indices can be used to reflect the needs of the system operators. When an award/penalty scheme is applied to the regulation of the system operators, their performance must be controlled, accounting for the power quality, security of supply and investment costs.

The rest of this paper is organized as follows: Section 2 describes the methodology for the stochastic assessment of investment efficiency. The application of the procedure on a case study and results are presented in Section 3. Finally, Section 4 summarizes the conclusions of the paper.

2. STOCHASTIC ASSESSMENT OF INVESTMENT EFFICIENCY IN A POWER SYSTEM

The proposed ranking procedure can be divided into three tasks as shown in Figure 1. The first task is the input data section, which includes preparation of the investment plan and preparation of scenarios using stochastic modeling, [17], and the MC technique, followed by the scenario-reduction procedure applying the K-MEANS clustering approach. The MC procedure is explained in detail in Subsection 2. 1. The scenario reduction procedure is discussed in Subsection 2. 2.

Once the network expansion plan is prepared and operating states determined, AC power-flow calculations are performed to produce information about the effects of new investment candidates on the existing power system, i.e. on the active-power losses, bus voltages and line loadings. This task is explained in Subsection 2. 3.

The final task is a cost (technical)/benefit analysis for each investment candidate. In this part indices *LEI* (Active-Power Loss Investment Efficiency Index), *VEI* (Voltage Profile Investment Efficiency Index) and

PEI (Active- Power flow Loading Mitigation Investment Efficiency index) are calculated, which examine the impacts of new investments on active-power losses, bus voltages and line loadings. Calculations of these indices are presented in Subsection 2. 4. In Subsection 2. 5 an optimization model for final decision making is proposed, considering the newly proposed indices.

Based on *LEIs*, *VEIs* and *PEIs* the investment ranking results in a priority list, indicating which investment merits an advantage considering its technical-economic benefit. In this way, electrical network planning part is improved, since it merges two important aspects valuable to making educated decisions regarding network expansion and reduce capital spending.

2.1. Input data preparation

The first subtask is a preparation of network investment plan that includes construction of new lines and also reinforcements in the existing electrical network depending on the needs, [18], and future forecasted injected demand and generation needs. Each investment candidate has its calculated economic and technical parameters.

The second subtask presents the modelling of a power system that includes a definition of network parameters and initial nodal generation and demand needs. Since the existing system is subjected to an upgrade, it is reasonable to be considered as a reference in the following assessment procedure, to gain information about the investment's effect.

The third subtask is stochastic generation of operating states. There are several approaches in creating operating scenarios. First approach is to involve past-data analysis and use excising scenarios. Second would apply contingency analysis (N-1) on existing scenarios and undertake the newly created. Third approach would be to combine the first two approaches. Also the probabilistic approach can be used to create scenarios when combined with past data to create new scenarios. Therefore, in the third subtask of this paper, probabilistic approach is used, the MC simulation [19], [20], [21], to generate numerous stochastic scenarios-operating states. The generated scenarios would also include the worst case scenarios i.e. scenarios that have low occurrence probability.

A set of random load values are generated according to the normal probability density function, *RN*, for *k*-th bus defined as:

$$RN_k \sim N(\mu_k, \sigma_k) \tag{1}$$

The load $D_{k,s}$ at *k*-th bus in *s*-th scenario, depends on *k*-th mean and standard deviation, μ_k and σ_k, respectively, which are defined based on the past-data analysis. It is calculated as:

$$D_{k,s} = \left(D_{k,0} + RN_k(\mu_k, \sigma_k)\right) \tag{2}$$

where $D_{k,0}$ presents the initial value of the load at *k*-th bus.

A discrepancy between power system demand needs in the initial and *s*-th scenario is proportionally allocated among generators regarding initial state generation. In this way, the power balance in the power system is maintained. This section considers the security constrained economic dispatch (SCED) calculations, [22], concerned with the allocation of the generation required among the generators available in order to meet demand needs and to satisfy the power system operating constraints. Also, using the SCED calculations the congestions are considered.

Each scenario has a specific topology as well. There are deterministic and probabilistic approaches to consider the outages i.e. the random (stochastic) nature of element outage. In [23], the outage possibility of the components is modeled as a deterministic criterion in expansion planning. However, the stochastic parameters in [24] and [25] are described with probability distributions. In this paper, probabilistic approach is used, since the scenario topology is created by applying MC simulation on known availability of lines and transformers. The availabilities are determined from available historical data on the outages of these elements in a power network. A uniformly distributed random number is defined in *s*-th scenario, which holds a value between $a = 0$ and $b = 1$, as follows:

$$RU_s = U(b, a) \tag{3}$$

The status of the element is set to 1 (in service) when the random value is less than the *e*-th element's availability A_e; otherwise, is set to 0 (outage):

$$\begin{cases} 1 \text{ (in service)}, & RU_s \le A_e \\ 0 \text{ (outage)}, & RU_s > A_e \end{cases} \tag{4}$$

The *e*-th element's availability is calculated as follows:

$$A_e = \frac{m_e}{m_e + r_e} \tag{5}$$

where the A_e represents *e*-th element's availability, m_e represents *e*-th element mean time to failure and r_e represents *e*-th element mean time to repair.

2.2. Scenario reduction using K-MEANS clustering tool

In this section, the set of scenarios, which can occur during the desired assessment period T, is reduced using the K-MEANS procedure, [26], [27], [28]. The scenario reduction is applied in order to speed up the assessment process. Each scenario in the reduced set of scenarios has its own probability of occurrence.

2.3. AC Power-flow simulation

The second section of the proposed procedure, in Figure 1, is an AC power-flow calculation for the initial operating state with no investment candidates and for all following scenarios with investment candidates, respectively. These calculations are performed for all SC scenarios obtained by the presented scenario reduction technique. Since the transmission losses, bus voltages and line loadings are addressed, an appropriate AC power-flow calculation method should be applied, e.g. the Newton-Raphson method. In this paper, AC model is included, since it considers the reactive-power i.e. the voltage levels. Also, the active-power losses are not neglected and can be completely analyzed. All together $SC \times IC$ calculations are performed leading to the final task - the cost/benefit analysis, as discussed in Subsection 2. 4. The notation SC stands for number of scenarios and IC for the number of investment candidates.

2.4. Cost/benefit analysis

In the final section of the proposed method, in Figure 1, the investment candidates are evaluated and ranked based on the ratio between the technical benefit and investment costs. Since a set of information is obtained about the effects of the proposed investment candidates, the decrease of the active-power losses due to the u-th investment candidate, in s-th scenario, is calculated as:

$$\Delta PL_u = \sum_{s=1}^{SC} \left(PL_{0,s} - PL_{u,s} \right) \cdot p_s \tag{6}$$

where $PL_{u,s}$ are overall active-power losses including the u-th investment candidate in s-th scenario and $PL_{0,s}$ are initial overall active-power losses in s-th scenario with no investment candidates and p_s is s-th scenario probability. In (6), it can be seen that is considered as a weight factor for s-th scenario. After all u-th investment candidate ΔPL_u are calculated the newly proposed LEI is calculated:

$$LEI_u = \frac{\Delta PL_u}{N_u} \ \forall \ u = 1, 2, ..., IC \tag{7}$$

where LEI_u represents the u-th investment candidate newly proposed investment efficiency assessment index that shows the unary relation due to the u-th investment candidate newly conceived active-power losses and its investment cost. N_u, is u-th investment candidate actualized investment cost (net present value), calculated as follows:

$$N_u = N_{u,n} \cdot \frac{1}{(1+d)^n (1+z)^n} \tag{8}$$

where $N_{u,n}$ stands for u-th investment cost in the explicit year n, d and z are discount and inflation rates, respectively. In this paper, the discount and inflation rate are taken to be constant. Thus, if two investment candidates are considered in the electrical network development plan, namely investment 1 to be implemented instantaneously and investment 2 to be implemented in 2 years, actualization of the investment costs must be used, since the value of the money invested i.e. investment costs in the present are worth more than the same amount in the future. This can be because of the inflation during the plan for the development of the electrical network. Accounting for equation (7), positive value of the index represents active-power losses decrease due to the inclusion of the u-th investment candidate and vice-versa.

The improvement of the electrical network voltage profile due to the u-th investment candidate is assessed as follows:

$$\begin{aligned} VP_{0,s} &= \sum_{k=1}^{NK} \left| V_{0,s,k} - V_{nom} \right| \\ VP_{u,s} &= \sum_{k=1}^{NK} \left| V_{u,s,k} - V_{nom} \right| \end{aligned} \tag{9}$$

where, $VP_{0,s}$ represents the sum of the absolute value of the differences between the voltage magnitude in the base case 0 in s-th scenario at k-th bus, $V_{0,s,k}$, and the ideal voltage magnitude V_{nom}, [29]. Also, the voltage at k-th bus, is compared with the ideal voltage value due to the insulation ageing concern [30], appearance of overvoltage occurrences, due to load switching, reactive power delivery or undervoltage conditions in the power network. $VP_{u,s}$ represents the sum of the absolute value of the differences between the voltage magnitude due to the u-th investment candidate in s-th scenario at k-th bus , $V_{u,s,k}$, and the ideal voltage magnitude V_{nom}. The NK stands for the total number of bus nodes. The improvement of the voltage profile due to the u-th investment candidate is assessed as:

$$\Delta VP_u = \sum_{s=1}^{SC} \left(VP_{u,s} - VP_{0,s} \right) \cdot p_s \tag{10}$$

Having the magnitude of the bus voltages closer to the nominal magnitude would reflect lower absolute difference, as noted in equation (9). Consequently, if the voltage profile is improved due to the u-th investment candidate, the value of delta ΔVP_u would be low or negative, equation (10).

Thus, VEI is defined as follows:

$$VEI_u = \frac{\Delta VP_u}{N_u} \ \forall \ u = 1, 2, ..., IC \tag{11}$$

Accounting for equations (9)-(11), lower value of the index VEI represents improvement of the voltage profile of the electrical power network due to the implementation of the u-th investment candidate and its investment costs.

Line loadings due to u-th investment candidate has been also assessed as follows:

$$\begin{aligned} PT_{0,s} &= \sum_{l=1}^{NL} \left(TTC_l - P_{0,s,l} \right) \\ PT_{u,s} &= \sum_{l=1}^{NL} \left(TTC_l - P_{u,s,l} \right) \end{aligned} \tag{12}$$

$$\Delta P_u = \sum_{s=1}^{SC} \left(PT_{u,s} - PT_{0,s} \right) \cdot p_s \tag{13}$$

where, $P_{0,s,l}$ represents the base case active-power flow in s-th scenario of the l-th line. TTC_l is l-th linetotal transfer capacity. $P_{u,s,l}$ is due to u-th investment candidate in s-th scenario l-th line active- power flow. NL stands for the total number power lines in the initial power system. $PT_{0,s}$ and $PT_{u,s}$ represent the overall excess capacity of the lines. Thus, PEI is defined as follows:

$$PEI_u = \frac{\Delta P_u}{N_u} \ \forall \ u = 1, 2, ..., IC \tag{14}$$

Increased (positive) overall excess capacity of the lines, due to u-th investment candidate, as presented in equation (12)-(14), represents mitigation of the active-power loadings.

In the final step, a priority list is yielded in decreasing order according to the calculated values of the individual indices LEI, VEI and PEI of u-th investment candidate. In comparison to the index values, the priority list is acquired as follows:

$$\begin{aligned} LEI_i &> LEI_j > ... > LEI_m \\ VEI_i &> VEI_j > ... > VEI_m \\ PEI_i &> PEI_j > ... > PEI_m \end{aligned} \tag{15}$$

LEI_i, VEI_i and PEI_i represent the i-th individual investment index value reflecting the biggest active-power losses decrease, voltage profile improvement and line loadings mitigation per monetary unit, respectively. LEI_j VEI_j and PEI_j are the next j-th investment index values to follow, up until the last m-th investment of the investment plan. The sequences of the individual investment indices in (15) can differ, which means that one investment can have distinctive effect considering the quantity that the investment efficiency index nurtures.

To explain the comparison of the cost-efficiency investment assessment regarding the individual index, LEI, VEI or PEI, the value of the selected investments is normalized for each investment strategy as follows:

$$\eta_{LEI_r} = \frac{\sum_{u=1}^{SI} LEI_u}{\sum_{u=1}^{IC} LEI_u} \tag{16}$$

where η_{LEI_r} is r-th investment strategy efficiency ratio regarding the LEI investment efficiency index, u is the investment candidate, SI is the number of selected investments according to the r-th investment strategy and IC is the total number of investment candidates. The same efficiency ratio, according to equation (16), is calculated for indices *VEI*, η_{VEI_r} and *PEI*, η_{PEI_r}. The total number of investment strategies is *R*.

2.5. Optimization model for final decision making

This section presents the optimization model that can be used for final decision making, with respect to the involved investment ranking criteria. It is the cost-efficient investment approach, subjected to the SOs desired network improvement level.

As mentioned, one of the possible applications of the indices elaborated, besides as ranking criteria, is to include them as constraints in an optimization model, with objective of minimizing the overall investment cost:

$$\sum_{u=1}^{IC} N_u \cdot x_u \to \min \tag{17}$$

subject to:

$$\boldsymbol{S} \cdot \boldsymbol{f} + \boldsymbol{g} = \boldsymbol{d} \tag{18}$$

$$\bar{\boldsymbol{g}}_{\min} \le \boldsymbol{g} \le \bar{\boldsymbol{g}}_{\max} \tag{19}$$

$$\bar{\boldsymbol{f}}_{\min} \le \boldsymbol{f} \le \bar{\boldsymbol{f}}_{\max} \tag{20}$$

$$\sum_{u=1}^{IC} LEI_u \cdot x_u \ge LEI_{SO} \tag{21}$$

$$\sum_{u=1}^{IC} VEI_u \cdot x_u \ge VEI_{SO} \tag{22}$$

$$\sum_{u=1}^{IC} PEI_u \cdot x_u \ge PEI_{SO} \tag{23}$$

$$x_u \in \{0,1\},\ \forall u = 1,2...,IC \tag{24}$$

Equation (17) minimizes the overall investment cost and offers optimal solution for final decision making. In the objective function x_u is the *u*-th investment candidate decision variable (binary), holding value of 1 if *u*-th investment candidate selected and 0, otherwise. N_u is *u*-th investment candidate actualized cost, as noted with equation (8). In equation (18), $\boldsymbol{S}$ is the branch-node incidence matrix, $\boldsymbol{f}$ is a vector with elements f_l (*l*-th line power-flow), $\boldsymbol{g}$ is vector with elements g_k i.e. *g*-th generator at *k*-th bus and $\boldsymbol{d}$ is a vector with elements d_k, i.e. *k*-th bus demand. In equations (19) and (20), the maximum limit values of the generators and lines (and transformers) are elements of the vectors $\bar{\boldsymbol{g}}_{\max}$ and $\bar{\boldsymbol{f}}_{\max}$, and the minimum limit values of the vectors $\bar{\boldsymbol{g}}_{\min}$ and $\bar{\boldsymbol{f}}_{\min}$, respectively. In (21), (22) and (23), LEI_{SO}, VEI_{SO} and PEI_{SO} are empirically identified values, set by SO in accordance with their needs, [31]. Constraint (24) defines binary variable for each investment candidate.

3. CASE STUDY

The newly proposed investment ranking criteria were tested using the standard New England test power system. New proposed investments are presented in Figure 2. Investment in network elements replacement is noted with dashed line and in construction with double-dot dashed line. Even though the presented method is tested on standard test power system it must be stressed that the method is in-general and can be applied to any other power system using different input data.

In accordance with equation (2), the mean value and the standard deviation rates at *k*-th bus, μ_k and σ_k are set to values 0 and 0.1, respectively. The overall number of busses is *K*= 39 (New England). In accordance with equations (1) and (2), load variation at an individual *k*-th bus is performed. Successively, the discrepancy in *s*-th scenario demand needs and generation was retained accounting for the SCED calculations and elements' availability. Overall, for each hour of an assessment period of *T*= 1 year, 8760 stochastic scenarios were created, reflecting a variety of possible operating states (even worst case) that can occur.

To speed up the assessment procedure, the overall number of stochastic scenarios *S*= 8760, was reduced to *S*= 10, using the K-MEANS reduction procedure. Each scenario has derived its probability of occurrence, as shown in Table 1. Of the reduced scenarios, the highest value of the scenario probability holds scenario no. 8 and its probability weight is p_8= 0.1147. The lowest probability weight holds scenario no. 5 and its probability weight is p_8= 0.0892.

In this case study, the SO is under PBR. Consequently, SO cost-efficient investment is advised to avoid penalization, imposed by the PBR regime. For that purpose, the SO uses the proposed method to assess proposed investments efficiency using probabilistic approach, thus, to select investment candidates so that to gain as much rewards, as also shown in [31]. Similar to the core research in [16] (on which this paper is based), an investment plan is proposed with 10 different investment candidates. The available investment fund is 600,000.00 €. This budget constraint can be also included in the involved optimization model (17)-(24). The investment candidates proposed in the investment plan are advised from employees-experts, experienced and on-field individuals. Also, the availability of right-of-way of the investment candidates is comprised. Budgetary constrained planning enforces SOs to invest within the available budget constraint and to spend the available budget in the best possible manner, [32]. At this point, the presented method comes in hand.

For the SO, five different investment strategies are advised. Strategy *A* is the initial investment strategy, which is an example of inefficient investment and used to show the advantages of the proposed ranking method applied in strategies *B*-*D*. The fifth, strategy *E*, uses the proposed optimization model for the final decision making, to show the practical appliance of the presented indices *LEI*, *VEI* and *PEI* as constrains in the traditional expansion planning optimization model.

- strategy *A:* SO undertakes maximum number of investments within the available investment fund (most in-common case of network investment),
- strategy *B:* SO undertakes the investment candidates with highest *LEI*s within the available investment fund,
- strategy *C:* SO undertakes the investment candidates with lowest *VEI*s within the available investment fund,
- strategy *D:* SO undertakes the investment candidates with highest *PEI*s within the available investment fund,
- strategy *E:* SO undertakes the investment candidates as a result from the optimization model.

Since the number of scenarios (reduced) $SC = 10$ and the number of proposed investment alternatives is $IC = 10$, overall, 10×10 AC power-flow simulations were executed, to obtain the effect of the new investments on active power losses, bus voltages and line loadings. Hence, using the u-th investment candidate actualized investment cost shown in Table 2, cost/benefit analysis was performed for each individual investment candidate in accordance with section 2.4. For this case study, it is assumed that all proposed investment candidates are implemented in the current year. As shown in Table 2, investment no. 4, has the highest investment cost and investment no. 10, the lowest.

Also, Table 2 shows the calculated values of the proposed indices *LEI*, *VEI* and *PEI* for all investment candidates, by following equations (7), (11) and (14). The positive value of the *LEI* and *PEI* indicate that the investment candidate has a positive inclusion effect on the power system, i.e. the investment candidate decreases the active-power losses or helps to mitigate the line loadings, respectively. Lower value of the index *VEI* indicates that the bus voltages are closer to the nominal value due to the new investment candidate. Consequently, the voltage profile with regards to the reference case of the electrical network is improved.

As previously noted, by following investment strategy *A*, the SO would undertake as much as investments within the investment fund. As shown in Figure 3, the selected investments are colored in black. This strategy is initial and used to show the advantages of the proposed investment strategies that follow cost-efficient investment. In the strategy *A*, the SO would undertake investments 10, 8, 9, 2, 1 and 3 with the total investment value of 528,500.00 €, which is within the available investment fund of 600,000.00 €. Investment by following strategy *A* is not cost-efficient, since it would include investment candidates without taking into account their effect on the initial state of the power system.

By following investment strategy *B*, as shown in Figure 4, the investment order would be 10, 6, 9, 5, 8, 2, 4, 3, 7 and 1 (*LEI*s value is sorted in descending order). There are not negative values, indicating that each investment candidate brings positive cost-efficient impact in decreasing the active-power losses. Since the investment fund is limited, it shortens the list to selecting candidates 10, 6, 9, 5, 8 and 2. Total investment cost of selected investments is 567,000.00 €. Investment selection (Figure 4, colored in black) by following investment strategy *B* ensures investments that would decrease at highest level the active-power losses per invested monetary unit. *LEI* is a measure showing the relative unary effect of the invested money on decreasing the active-power losses. In other words, the ranking gives an advantage to investment candidates that have a higher effect on lowering the active-power losses in the power system per monetary unit. The most positive effect on power system, regarding the active-power losses per invested monetary unit holds investment no. 10.

Investment strategy *C* follows the investment order by giving advantage to investment candidates with a lower value of *VEI*. The investment order would be: 10, 7, 6, 1, 2, 5, 8, 4, 9 and 3 as presented in Figure 5. The selection reduces to investments 10, 7, 6, 1, 2 and 5 (colored in black, Figure 5). Investment selection amounts to

597,000.00 €. Including this investment strategy according to the proposed ranking list of *VEI*, would ensure improvement of the voltage profile in the power system. Investment no.10 has the most positive effect on improving the voltage profile of the power system.

In investment strategy *D* lines loadings are regarded. The SO would select investment candidates that have the highest impact on line loadings mitigation. Advised investment in descending) order would be investments 4, 3, 5, 10, 9, 6, 8, 7, 1 and 2, as shown in Figure 6. It can be noticed that the value of the investment candidates 1, 2, 6, 7 and 8 is negative, which means that these investments would bring additional loading in the network. Following strategy *D*, the SO would include investments 4, 3, 5 and 10, colored with black in Figure 6. These advised investments would cause loadings relive to the power network. The most positive effect in this case holds investment no. 4.

Investment strategy *E* follows the proposed optimization model for final decision making. In this strategy, the budget is unconstrained and it would include investment candidates shown in Figure 7- colored with black. The optimization model was solved using mixed-integer linear programming (MILP). The empirically identified values of LEI_{SO}, VEI_{SO}, and PEI_{SO}, that are set by the SO are 3.0484e-05 MW/€, 4.2586e-07 kV/€ and 3.7420e-04 MW/€, respectively. In this case study, these values reflect the needs of the SO i.e. the desired level to be achieved of overall investment on the active-power losses decrease, voltage profile improvement and line loadings mitigation. The optimization model yields the selection of investments 3, 4, 8, 9 and 10. The value of the objective function (minimum) in this case is 636,500.00 €.

The comparison of different investment strategies is presented in Table 3. From the comparison table, it can be concluded that by following strategy *A*, the number of realized investments would be **6** and the sum of *LEI*s, *VEI*s and *PEIs* would be 3.2862e-05 MW/€, 4.47e-07 kV/€ and -3.2927e-05 MW/€, respectively. By following investment strategy *B*, the number of realized investments would be 6 and the sum of *LEIs*, of the selected investments is equal to 4.6631e-05 MW/€. The value of *VEI*s, of the selected investments in strategy *B*, is 1.6573e-07 kV/€ and on *PEIs*, is -1.2519e-05 MW/€. By following investment strategy *C*, the number of included investments would be 6 and the sum of *VEI*s of included investments equals to 5.1917e-08 kV/€. For the same investment candidates as proposed in strategy *C*, the overall value of *LEI*s is 3.3753e-05 MW/€ and of *PEIs* is -6.2386e-05 MW/€. In strategy *D*, the number of included investments is 4, and the sum of *PEIs* of the included investments is 8.0341e-04 MW/€. The values of the *LEIs* and *VEIs* of the selected investments, by following strategy *D*, is 2.4045e-05 MW/€ and 3.5938e-07 kV/€, respectively. It must be emphasized that even though the number of included investments is the same in strategies *A*, *B* and *C* smaller in strategy *D*, the decrease of the active-power losses, improvement of the voltage profile and line loadings mitigation is higher, in comparison to strategy *A*, as a consequence of following the proposed method.

To see which investment strategy is most advised for the SO, in accordance with equation (16), the investment strategy efficiency ratios were calculated. The comparison of the investment strategy efficiency ratios is presented in Table 4. The individual investment strategy efficiency ratio value regarding the *LEI*, *VEI* and *PEI* indices are presented in Figure 8 - Figure 10. As the strategy *B* undertakes the investment candidates with higher value of the index *LEI*, it can be seen, that the value of the investment strategy efficiency ratio is highest (0.9237), as shown in Figure 8, black marked. Next to follow are strategies *A* (0.6509), *E* (0.6338), *D* (0.4763) and *C* (0.6686). Considering *VEI*, investment strategy *C* has the lowest investment strategy efficiency ratio (0.0987), implying to undertake the selected investment candidates to improve the voltage profile, Figure 9, black marked. The value of this investment strategy efficiency ratio is lower than the others, since *VEI* considers investment candidates with lowest *VEI*s, consequently the investment strategy ratio is lowest. Next to follow are strategies *B* (0.3152), *D* (0.6834), *A* (0.8500) and *E* (0.8900). Regarding the index *PEI*, it can be seen that the values of strategies *A*, *B* and *C* are negative: -0.0488, -0.0186 and -0.0925, respectively. As anticipated, investment strategy *D* has the highest investment strategy efficiency ratio, 1.1916, regarding the index *PEI*, since it undertakes the investment candidates with higher *PEI* value, Figure 9, black marked. Next to follow are investment strategies *E* (1.1023), *B* (-0.0186), *A* (-0.0488) and *C* (-0.0925). Summing the individual investment strategy efficiency rations regarding *LEI*, *VEI* and *PEI*, gives the overall investment strategy efficiency. Therefore, investment strategy *E* is the most advantageous (2.6261); next to follow are *D* (2.3514), *A* (1.4521), *B* (1.2203) and *C* (0.6748).

4. CONCLUSIONS

After closely examining the inclusion of the new investments in electrical power network, it is clear that investment efficiency assessment is needed for cost-efficient investment when an award/penalty regulation scheme is applied to the regulation of the system operators. By enhancing the investment efficiency assessment by also engaging a stochastic approach in operating states creation, this paper proposes new investment criteria likely to improve the investment ranking process which is a vital component of the electrical network expansion planning. The ranking criteria are based on examining the effect of new investments on active-power losses, voltage profile and lines loadings by showing the relative unary effect of the invested money on network improvements. Additionally, the paper proposes an optimization model for final decision making. The stochastic assessment of the investment efficiency is based on the newly proposed indices *LEI, VEI* and *PEI*, which represent ratios between the decrease of the active-power losses, improvement of the voltage profile and the line loadings mitigation due to the investment candidate and its actualized initial investment costs, respectively. A defined number of stochastically modeled scenarios, for a defined assessment period *T* were created, thus, using the K-MEANS scenario reduction procedure reduced to a predefined number of scenarios used to see the effect of the investment candidate. The effects of the investment candidates on decreasing the active-power losses, improving the voltage profile and line loadings mitigation were simulated by performing AC power-flow simulations using the stochastic scenarios. Stochastic indices used to assess investment efficiency were calculated by including the probability of the individual stochastic scenario. The method for cost-efficiency investment is demonstrated on a standard IEEE test system, whereby according to three different strategies of investment, the stochastic indices were used in the planning process to assess the efficiency of the investment candidates, and thus ranked, revealing which investment candidate should be favored; therefore, used in the next part for decision making, when insufficient investment funds exist. Another investment strategy was also involved, which used the proposed optimization model for final decision making. By undertaking the proposed procedure in the performance based model of regulation where the penalty/reward scheme is applied, the SOs would follow an order of cost-efficiency investment, which will increase incomes and improve the power quality supply for the customers, decrease the active-power losses and line loadings in the power system. The contribution of this research also favors the ability of the national energy regulator to define the reward and penalty areas in the mathematical model of the performance based payment structure and also for retirement and replacement investment decisions. Also, the method can be used as a fact-argument in supporting the network development and planning strategies. SOs' long term strategies comprise maintenance and improvement of the network reliability level, improved quality of service, constant power quality, integration of renewable sources of electrical energy etc. The incorporated investment efficiency assessment indices offer a diversity of investment selection and realization based on SOs' strategic interest of network development. We offer a method that can be included in the short-term and long-term allowed return forecasts and penalty evade, since, in general, the SOs perform in performance based regulation environment.

The outlined procedure conceives future research which would combine in one criterion a wider scope of technical-economic quantities where each would have different weight. Therefore, the next challenge would be to determine the weights and incorporate new investment criterion used in the ranking procedure for increased cost-efficiency of the proposed investment plan. Also other optimization models for final decision making would need to be developed which would be subjected to the newly developed indices.

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FIGURE CAPTIONS

Figure 1: Flowchart of the proposed investment efficiency method
Figure 2: New England test system with investments
Figure 3: Undertaken investment candidates in strategy *A*
Figure 4: Undertaken investment candidates in strategy *B*
Figure 5: Undertaken investment candidates in strategy *C*
Figure 6: Undertaken investment candidates in strategy *D*
Figure 7: Undertaken investment candidates in strategy *E*

TABLE CAPTIONS

Table 1: Scenario number and its probability of occurrence
Table 2: Comparison of investment candidates
Table 3: Comparison of investment strategies
Table 4: Comparison of investment strategy efficiency ratios

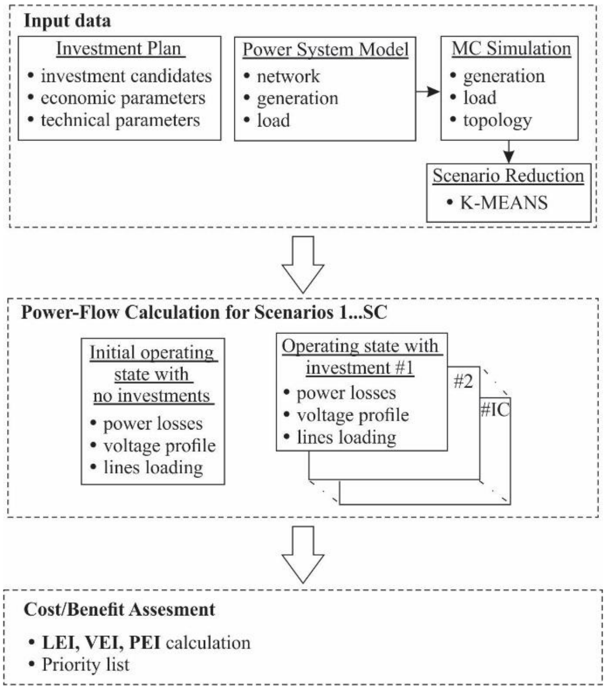

Figure 1: Flowchart of the proposed investment efficiency method

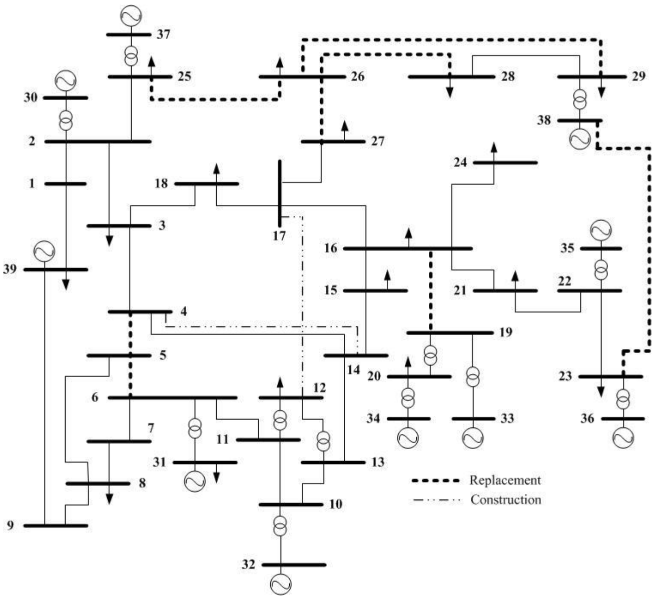

Figure 2: New England test system with investments

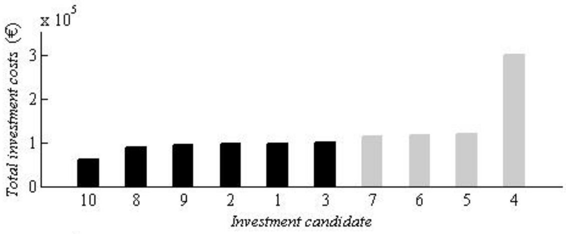

Figure 3: Undertaken investment candidates in strategy *A*

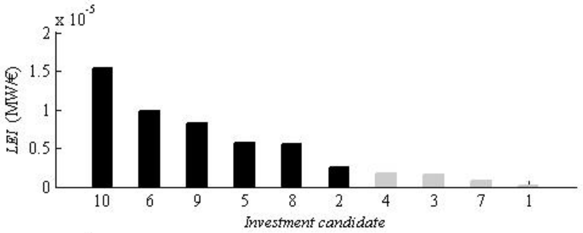

Figure 4: Undertaken investment candidates in strategy *B*

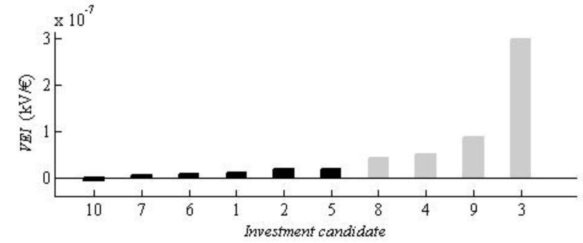

Figure 5: Undertaken investment candidates in strategy *C*

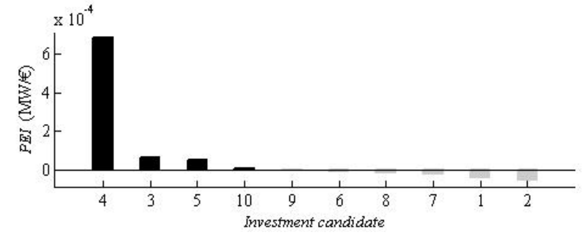

Figure 6: Undertaken investment candidates in strategy *D*

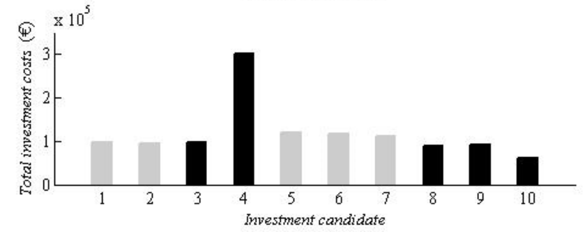

Figure 7: Undertaken investment candidates in strategy *E*

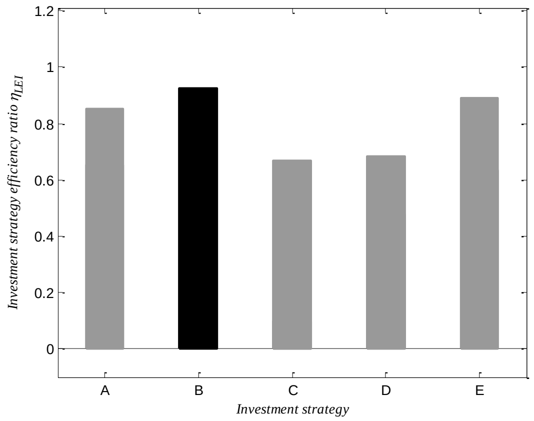

Figure 8: Investment strategy efficiency ratio value regarding the *LEI* index

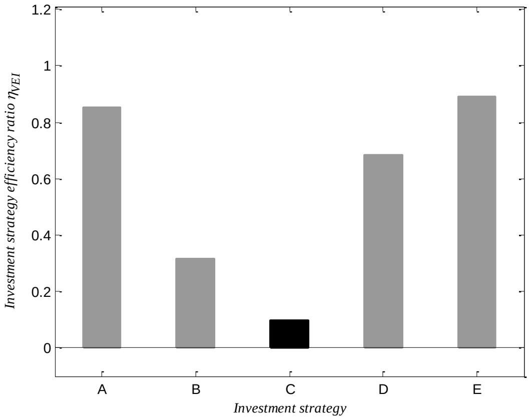

Figure 9: Investment strategy efficiency ratio value regarding the *VEI* index

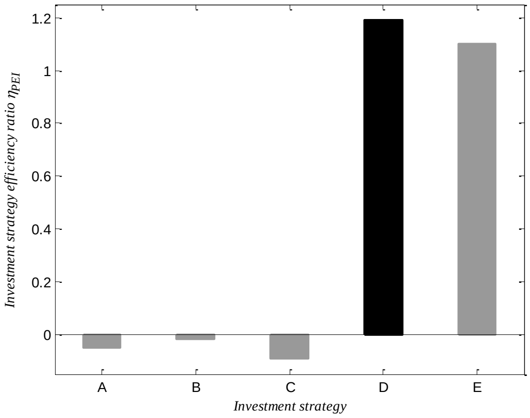

Figure 10: Investment strategy efficiency ratio value regarding the *PEI* index

Table 1: Scenario number and its probability of occurrence

Scenario number	Probability of occurrence
1	0,1138
2	0,1117
3	0,1089
4	0,0892
5	0,0795
6	0,1032
7	0,0966
8	0,1147
9	0,1023
10	0,0796

Table 2: Comparison of investment candidates

Investment candidate	N_u (€)	*LEI* (MW/€)	*VEI* (kV/€)	*PEI* (MW/€)
1	97,000.00	1.0251e-08	1.0481e-08	-3.9627e-05
2	95,000.00	2.5040e-06	1.7717e-08	-4.9569e-05
3	97,500.00	1.5442e-06	2.9722e-07	6.0535e-05
4	300,000.00	1.6484e-06	4.9240e-08	6.8688e-04
5	118,000.00	5.5886e-06	1.8820e-08	4.9427e-05
6	115,000.00	9.7355e-06	7.6067e-09	-8.1110e-06
7	112,000.00	6.5024e-07	3.1958e-09	-2.1074e-05
8	87,000.00	5.4363e-06	4.1272e-08	-1.1430e-05
9	92,000.00	8.1028e-06	8.6215e-08	5.9574e-07
10	60,000.00	1.5264e-05	-5.9034e-09	6.5683e-06
Sum		5.0484e-05	5.2586e-07	6.7420e-04

Table 3: Comparison of investment strategies

Investment strategy	Strategy *A*	Strategy *B*	Strategy *C*	Strategy *D*	Strategy *E*
Investment fund (€)	600,000.00	600,000.00	600,000.00	600,000.00	Unconstrained
Realized investments	**10, 8, 9, 2, 1, 3**	**10, 6, 9, 5, 8, 2**	**10, 7, 6, 1, 2, 5**	**4, 3, 5, 10**	**3, 4, 8, 9, 10**
Overall inv. costs (€)	528,500.00	567,000.00	597,000.00	575.500,00	636.500,000
$\sum_{u=1}^{SI} LEI_u$ (MW/€)	3.2862e-05	**4.6631e-05**	3.3753e-05	2.4045e-05	3.1996e-05
$\sum_{u=1}^{SI} VEI_u$ (kV/€)	4.4700e-07	1.6573e-07	**5.1917e-08**	3.5938e-07	4.6804e-07
$\sum_{u=1}^{SI} PEI_u$ (MW/€)	-3.2927e-05	-1.2519e-05	-6.2386e-05	**8.0341e-04**	7.4315e-04

Table 4: Comparison of investment strategy efficiency ratios

Investment strategy	Strategy *A*	Strategy *B*	Strategy *C*	Strategy *D*	Strategy *E*
η_{LEI_r}	0.6509	0.9237	0.6686	0.4763	0.6338
η_{VEI_r}	0.8500	0.3152	0.0987	0.6834	0.8900
η_{PEI_r}	-0.0488	-0.0186	-0.0925	1.1916	1.1023
Sum	1.4521	1.2203	0.6748	2.3514	2.6261