

EVALUATION OF SYSTEM PROTECTION SCHEMES, WIDE AREA MONITORING AND CONTROL SYSTEMS

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ABSTRACT

Market and environmental constraints force power systems to be operated closer to their limits and utilize the existing assets much better. To achieve this while keeping high security is a challenging task. Various technical solutions fulfilling this mission have recently been proposed. The benefits they bring are both of security and financial natures. Their quantification is strongly dependent on the particular conditions of the system. In this paper a systematic framework for their assessment will be given.

I. INTRODUCTION

Growing load demand simultaneously with an ongoing deregulation of electricity markets in many countries often lead to the stresses of transmission systems and their operation very close to their limits. Power systems are then more sensitive to failures that occur and limits for a maximal transmission through some corridors of the network are reached. Therefore an interest of many researchers focuses on tools, systems and solutions helping to handle this situation.

If available statistics are analyzed it is found that the overwhelming majority of causes for individual loads not being supplied can be found in the distribution systems. Typically it can be said that more than 95% of the outages are caused by failures in systems of voltage 130 kV and below, [1]. However, these failures have almost always a very local impact and no serious consequences are experienced by the society in large. Furthermore, the restoration of faulted parts is straightforward and standard. Faults in transmission system leading to more widespread load outages are very rare in most power systems, but if they occur they can have serious impacts on many activities in society. If a whole city or part of a region suffers a black out, the economic and societal impacts can be very significant, and consequently the requirements on security must be much higher in the transmission system as compared with the distribution level. There is an increased dependence of supply of

electric power from other infrastructure systems, [2]. Furthermore, the restoration after a major transmission system fault is a very complicated and laborious task. In stressed power system the risk of cascading events is of particular concern. Through cascading, the consequences of a single event can be spread over large geographical distances in a system. Hence, there is a need to assess and evaluate different means of improving transmission system security. Wide Area Monitoring and Control concepts (WAM&C) have been recently proposed as one such means.

This paper discusses the technical aspects of WAM&C tools for improving transmission system security only briefly. The main intention is to assess the benefits of these tools in a systematic way and to demonstrate their effectiveness from an economic point of view. In the evaluation we adopt the perception of the transmission network operator, e.g. ISO/TSO or a vertically integrated utility.

The paper is structured as follows. First a financial model for the assessment of WAM&C systems is proposed, to set a consistent framework for the overall evaluation. Then the tools' characteristics as possible technical solutions for the elimination of transmission systems weak points are discussed. The paper is concluded with an outline of the future work.

II. OVERALL ASSESSMENT PROCEDURE

For the assessment of the different technical solutions of improving transmission system security we will in a first step define the financial evaluation model. Following this assessment sequence, the reliability computations and simulations of the respective systems can be developed to deliver a consistent set of input data for the financial modeling. The evaluation scheme is displayed in figure 1. It can be read that we will generally consider two measures for improving power system security, where the focus is on the latter:

- inclusion of additional transmission capacities
- installing of a Wide Area Monitoring and Control System (WAM&C)

Technical aspects of either the building of new

transmission capacities or the installation of a WAM&C in power systems are outlined in section IV. For the introduction of the financial model, the approaches are only considered as two competing investment alternatives.

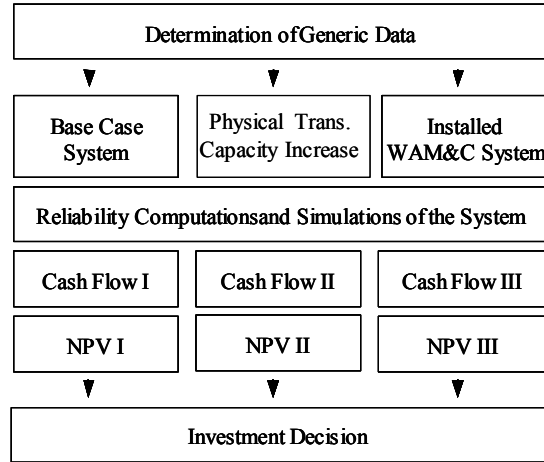


Figure 1: Evaluation Scheme

III. FINANCIAL ASSESSMENT

For the understanding of the financial model it is crucial that we consider a stochastic approach to evaluate the influence of a WAM&C system onto the power systems' performance (see section IV). Thus, it is obvious that the monetary outcome of the investment, i.e. the future cash flow is as well a stochastic value. This is, on the one hand due to the probabilistic nature of possible network failures, on the other hand, the external framework in which a company operates is highly complex and therefore subject to information uncertainty (e.g. the development of the capital and assets markets, taxation law, development of competing or partnering enterprises etc.). As we only outline the general procedure for evaluating WAM&C system, we will not consider the uncertainty in financial data.

A. General Objective

According to [3] investing means steering in between a triangle of cost, benefit and time as displayed in figure 2.

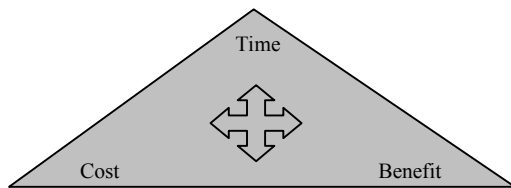


Figure 2: Investment Triangle [3]

The benefit may additionally be distinguished into non-monetary and monetary benefit, where for the

following assessment only the latter is considered. The simplification is done with respect to the current lack of data, representing factors as image improvements, customer satisfaction etc., although these soft factors are claimed to gain importance in recent years [4]. With the above assumptions two main business strategies can be figured out. Consider the elementary equation 1, where the monetary benefits from figure 2 are synonymous to revenue.

$$\Pi = p \cdot q - c(q) \quad (1)$$

As the price p can be assumed fix due to the regulation of the network operating company, profit Π may be improved by either a total increase of transmitted energy q or by a reduction of cost $c(q)$. The first strategy is to be followed by providing additional transmission capacity. As the installation of WAM&C protects the transmission system against the spreading of disturbances and their negative consequences, i.e. blackouts, the implementation of WAM&C promotes above all a reduction of fallacy cost. The dependency of revenues and costs within the two proposed strategies will be studied below.

B. Monetary Assessment

The essential questions to answer are: Does an increase in transmitted energy compensate for the cost of investing into a FACTS or a new line¹ or does a decrease of fallacy cost justify the installation of WAM&C systems and – when both alternatives are conceivable - which is to be favoured over the other. As displayed in figure 2, the third crucial factor for an investment project (besides costs and revenues) is time, i.e. the time value of money. Because of the long-term investment character² of either the building of a new line or the installation of a WAM&C system, the monetary value of the project has to be considered over the whole utilization time. Thus, a dynamic, multi-period approach is suggested for investment evaluation. In contrast to static, single-period methods the expected future cash flows are discounted to their present value. In the following we propose the net present value (NPV) as practicable method for assessing the investment decision [5]. The definition of the NPV is straightforward (equation 2).

$$C_0 = -I_0 + \sum_{t=1}^n (R_t - E_t) \cdot \frac{1}{(1+i)^t} \quad (2)$$

with:

C_0	net present value
I_0	initial investment cost

¹ We assume the building of new lines to be generally possible for evaluation purposes, despite of the high likelihood of public resistances.

² The usual amortization period for transmission lines over 50kV is 35 years, for WAM&C it is expected to be 15 years. (German taxation law)

R_t	revenues in period t
E_t	expenses in period t
i	discount rate

The determination of the input data will be closer looked at in the respective below paragraphs.

C. Initial Investment Cost

Initial investments are determined by the acquisition cost, i.e. the cost for the building of the transmission line or the installation of WAM&C system. Later occurring costs are included into the expenses.

D. Interest

Following the definition in [6] for the NPV a perfect capital market is assumed. Thus, interest rates for equity and outside capital are not distinguished. This assumption may be removed by using the approach of the Weighted Average Cost of Capital (WACC), which considers the cost of debt and equity [7]. For investment evaluation the cost of capital plays a crucial role. Interest rates must be determined with respect to the specific market- and company structure. As we only propose an assessment guideline here, it is not reasonable to give concrete figures.

E. Taxes

For the evaluation of taxes equation 3 has to be modified as follows:

$$C_0 = -I_0 + \sum_{t=1}^n [(R_t - E_t) - s(R_t - E_t - D_t)] \cdot q_s^{-t} \quad (3)$$

with:

D_t	expenses in period t
s	tax rate
q_s^{-t}	discount factor after tax in period t

Generally, tax expenses are deducted from the revenues. The cash flows are to be discounted with the after tax discount factor, where the specific rate depends on the governmental regulation within the respective country.

F. Revenues and Expenses

For the computation of the NPV the most essential input data is the estimated revenues and expenses over the planned amortization period. As future cash flows are dependent on the technical characteristics of the WAM&C tool and the potential influence on the system, revenues and expenses will be in detail looked at in sections IV paragraphs A to F.

G. Investment Decision

The investment decision is straightforward. Any NPV greater than zero will be beneficial as the future cash flows will contribute to the company's value. For the different investment alternatives the one with the highest NPV is to be chosen. With respect to figure 1 the decision is whether to invest in

additional transmission capacity or in a WAM&C system. It may be also conceivable that the system is better to stay unchanged. In case of little differences between the respective NPV values, non-monetary benefits come into place. Ecological and image-related considerations are nowadays gaining importance as the public claims growing interest into companies' activities. Thus, non-monetary benefits should be explicitly considered, when the monetary assessment delivers no definite solution [8].

H. Conclusions

In the above section we proposed a financial scheme for the evaluation of different investment alternatives within a power system. The definition was straightforward. Technical characteristics have not been discussed. This will be overcome in the following section, where we outline the influences of WAM&C systems onto a power system's performance and from that, the effect on the future cash flows. Section IV starts with an estimation of the reduction potential for transmission restrictions.

IV. POTENTIAL FOR REDUCTION OF TRANSMISSION RESTRICTIONS - OVERVIEW OF THE TECHNICAL MEANS

Transmission system operation restrictions can be expressed mainly in terms of transmission capacity and transmission availability. Both of them are closely related to the power system security.

An extension of the transmission system is a traditional way how to increase transmission capacity and decrease risk of failures resulting from the overloading of the network. This extension usually means building of new lines or another assets, e.g. FACTS devices.

Another way is the better utilization of existing assets and improved handling of the network failures (both reduction of the risk that they will happen and their elimination and stabilization of the power system operation). The trends are aiming to this category [9]-[17], so we will discuss and focus on this.

New emerging technologies in the area of wide area monitoring and control aim mainly into two directions. The goal of the first one is the increase of the transmission capacity in particular transmission corridors, mainly between two different electricity markets or reducing the congestion within one electricity market. This topic has been studied in [11]. The second purpose of introducing new wide area monitoring and control systems is to protect the transmission system against the spreading of disturbances and their negative consequences, i.e. blackouts. In the following we will focus on this purpose. One of the major considerations in this case

is the level of conservatism and level of the accepted risk in the power system operation. The majority of the utilities operate the network according to N-1 criteria. However, facing new situations (mainly deregulation of the electricity market and thus minimal possibility to influence the generation dispatch and resulting operation of the system under the conditions for which it has not been designed) forces some utilities to employ N-0 criteria, to accept the higher risk and reinforce their monitoring, protection and control systems.

However, irrespective of if an N-1 or N-0 criterion is used, the rules for operation of power systems are defined under assumption of many uncertainties, which lead to significant margins and conservative approaches to secure safe system performance. If some of these uncertainties can be eliminated, the operating point could be shifted with an insignificant increase of the risk.

To mention just one of those, loading of the lines can serve as a good example. If the maximal power flow in a line is not constrained by any stability concern, then the heating of the line by flowing current sets the limit. This limit is predefined for very inconvenient conditions – high ambient temperature and no wind, i.e. no cooling factors. But this is a very rare situation, so most of the time the line transfer limit is higher in reality [11], [13]. A largest space for elimination of operation uncertainties is in adjusting the operation conditions to the actual conditions in the network, i.e. on-line determination of the network margins from the stability and transmission capacity point of view. Various recently proposed methods and systems focus on this, ranging from precise monitoring of the power system stress, to the emergency control [12], [16] and [17]. The most relevant will be discussed more in detail. Referring to the equations (2) and (3), the initial investment represents the acquisition price of the WAM&C system. This figure can directly contain the service contract for the system lifetime, if not, the service costs must be included in the costs E_t .

The installation of WAM&C may intend to mitigate various dangerous phenomena that occur in power systems. We list here WAM&C by the phenomena together with the indication of the possible increase in revenues and introduced costs.

Power oscillations, also referred as power swings

WAM&C: On-line monitoring of the power oscillation modes could be used for on-line tuning of Power System Stabilizers to achieve the best performance reacting to the actual conditions in the network. Although the qualitative benefit is obvious, its quantification is very difficult. However, it has been shown that the installation of the damping controller in HVDC connecting Sweden and Finland

in the south has helped to increase the transfer through the northern AC connection between these two countries by 400 MW.

Alternative, present solution: The parameters of Power System Stabilizers (PSS) are tuned off-line. Since PSS should properly operate under all possible conditions that can occur, the robustness is the main requirement. However, the performance has then to be compromised.

Revenue/Cost Reduction:

- safe increase of the transfer between the distant areas

Angular Instability

WAM&C: References [18] and [19] propose the on-line solutions. Both of them use as a control action disconnection of affected generator.

Alternative, present solution: Out-of-step local relay shall disconnect the affected generator. One day ahead scheduling of the generation can reveal the risk of angular instability, but it is based on the one-day prediction, which may substantially differ from actual operating conditions that are later in the system. Angular instability risk is also one of the main issues to be considered in planning stage of power system extension. The estimation of the monetary benefit is very difficult in this case.

On-line thermal rating of the lines

WAM&C: The solution mentioned in [11] uses only measured electrical quantities, [13] describes already available products processing the weather data and current measurement.

Alternative, present solution: Today's practice is off-line limit set the way leaving certain safety margin for operation of the line under any circumstances, i.e. inconvenient ambient conditions, thus yielding quite conservative limit.

Revenue/Cost Reduction:

- increase of the power transfer with a minimal increase of the risk

Cost:

- human processing of the weather data (depending on the method)

Frequency Instability

WAM&C: The algorithm proposed in [12] monitors the status of the power plants (if they are connected or disconnected as a consequence of a contingency), and in case of a contingency quickly predicts the final frequency after the settling down of transients after a disturbance. This is done using the simplified load models dependent on voltage and frequency change, what is completely disregarded in case of local protection (under frequency relays). If this predicted frequency deviates too much from the desired one, appropriate actions are taken to restore the frequency. These actions can reflect/consider

present network situation, and are coordinated (i.e. only necessary amount of load is shed and at the most suitable locations) and can be executed as soon as the dangerous situation is identified and the needed input data are processed.

Alternative, present solution: Automatic Generation Control (AGC) corrects the minor frequency deviations caused by the slow dynamics like day load fluctuations etc. Under frequency load-shedding relays shall operate in case of more dramatic decreases in the frequency, typically a sudden load increase, or more often loss of the generation. They react to the drop of the frequency under the certain specified level and/or the decrease of the frequency with the sharper rate (df/dt) than specified.

Revenue/Cost Reduction:

- avoiding blackout (in extreme cases), thus no restoration etc.
- employment of the “cheap” control first (tap changing, change of the generator setting, FACTS setting, load shedding last)
- selection of the control means based on the weighting impact and cost of the control, if WAM&C designed such a way
- selective load shedding if unavoidable
- only necessary load shedding (reduction in the amount of shed load)

Cost:

- redispatch in emergency situations
- undelivered energy (due to load shedding, however less than without WAM&C)

Voltage Instability

WAM&C: Perhaps the most suitable field, since the phenomenon of voltage instability can be solved locally only to a limited extent.

Alternative, present solution: Under voltage load shedding relays take into account only the magnitude of the voltage in the node they supervise. But this is in many cases not the real measure of the voltage instability. Also the tuning and especially the co-ordination of the load shedding is a very difficult task. In the slower cases an appropriate operator action can avoid voltage instability. However, this is strongly dependent on the operator experience to recognize the danger from the available data provided by SCADA and/or EMS.

Revenue/Cost Reduction:

- avoiding blackout (in extreme cases), thus no restoration etc.
- employment of the “cheap” control first (tap changing, change of the generator setting, FACTS setting, load shedding last)
- selection of the control mean based on the weighting impact and cost of the control, if WAM&C designed such a way
- selective load shedding if unavoidable

- only necessary load shedding (reduction in the amount of shed load)

Cost:

- redispatch in emergency situations
- undelivered energy (due to load shedding, however less than without WAM&C)

V. CONCLUSIONS AND FUTURE WORK

An increase of the transmission system capacity as well as security is traditionally achieved by an extension of the system, e.g. building a new line. This solution offers very high reliability and availability (in terms of time) in basically all regimes of the system operation. However, it requires a very high initial investment, which makes it feasible/reasonable only in case of a high utilization.

In contrary, investment into WAM&C can be justified when a lower utilization rate is expected and the security concerns of the network solvable otherwise in a very limited extend are raised. In addition to a direct monetary cost benefit from WAM&C operation mentioned above, the installation of WAM&C could bring additional benefits, e.g. support in the future system extension planning decisions etc. All these aspects should be considered. Here we discuss only the qualitative features, possible costs and benefits. Their quantification is very individual for each power system.

However, a generally valid framework could be developed employing a probabilistic approach according to figure 1. The modelling techniques for the Simulation of a Reliability Test System are subject of the present and future study and implementation by the authors. Modelling of black outs in [20] and [21] includes both types of dynamics, i.e. slow – daily load random variation and random occurrence of the transmission components failures. However, the more applicable modelling is described in [22] under the term (in the chapter) “Security Considerations in Composite System Adequacy Evaluation”. We propose the following flowchart expressing the power system behaviour model processing the sample-by-sample input data. A challenging task is modelling of the action in case of encountered instability. Referring to figure 1, the action shall represent in the basic and the system extension (line building) cases the relay or/and operator decision, whereas in the WAM&C case their engagement. Regardless of the case, a faulty decision probability has to be considered as well.

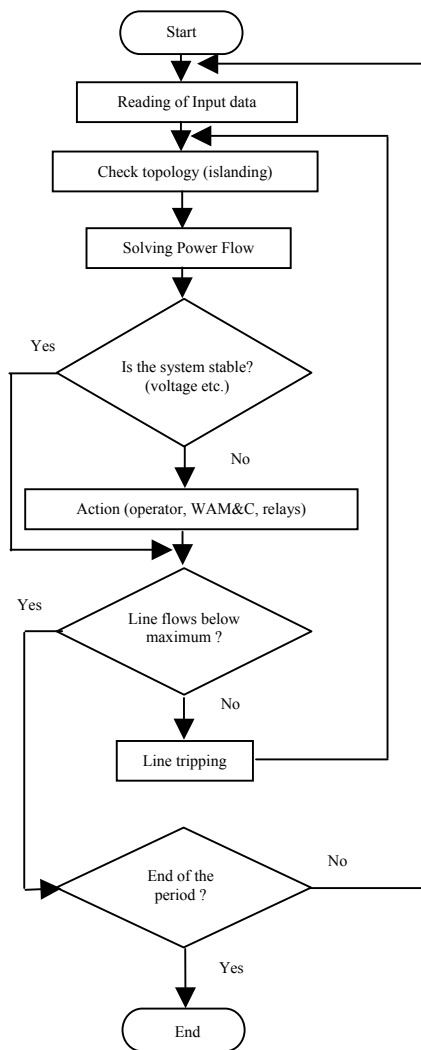


Figure 3: Principle flowchart reproducing the physical behavior of the power system

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