Performance Analysis of Smart Grid Solutions in Distribution Power Systems

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Abstract: Smart grid solutions are considered as a set of automation and telecommunication equipment connected to an intelligent master system, with aim to provide higher energy efficiency, optimized grid control and data processing. If applied in a power distribution network, it would include a wide set of smart applications for efficient operation, analysis, fault management, planning and optimization of grid operation. Together with field automation, as substation automation, feeder automation, remote terminal units and communication links, they constitute distribution automation management systems to provide higher efficiency and reduce cost of grid operation. In this paper, benefits and costs of a distribution automation management system is investigated and evaluated. The performance analysis is conducted considering the lifetime of the system, to manifest the profitability of the solution.

Keywords: Power Distribution; Smart Grid; Energy efficiency; Power system economics

1 Introduction

Opening of the electricity market and new regulations caused unbundling of vertically organized utilities into different companies, in the competitive market (e.g. generation, energy trade) or in further regulated (e.g. power transmission and distribution activity). Regulated power transmission and distribution companies (RPC) faced significant reduction of revenue (without energy trade) and increase of responsibility and penalties by regulation. In the new economic and technical environment, RPC are forced to significantly increase efficiency and reduce cost of operation, to be able to survive and operate positively. Smart Grid Solutions (SGS) provides this affect and are widely applied by RPCs. The challenge is quantification of benefits provided by SGS and comparison with related costs, to estimate the real profitability of such investments.

Power companies nowadays, implement different components of SGS with a common goal to increase efficiency of grid operation and reduce power losses, outage time and maintenance cost [1]–[4].

SGS are considered as set of advanced technologies aimed at improving the efficiency of grid operation, significantly improving reliability, quality and efficiency of power delivery, as well as reducing costs of power network operation. SGS include various technologies, as presented in Figure 1:

- *Smart Grid Control*: IT technologies applied in control centres of transmission or distribution companies, such as Advanced Distribution Management Systems (ADMS) for smart grid control, AMI/MDM for smart meter data management, Demand Response for management of consumption, GIS and Asset Management for asset data processing, etc.
- *Smart Power Grid:* operation technologies (OT) applied in power grid for automation of local operations (field automation systems): Substation automation systems, Remote Terminal Units (RTU), controllable Ring Main Units (RMU), Re-closers, Distributed Generators control, Electrical Vehicles management, Energy Storages control, etc,
- *Smart Consumption*: local control systems for smart management of energy consumption, as Building Management Systems, Industrial Control, Home Automation with smart meters, etc.

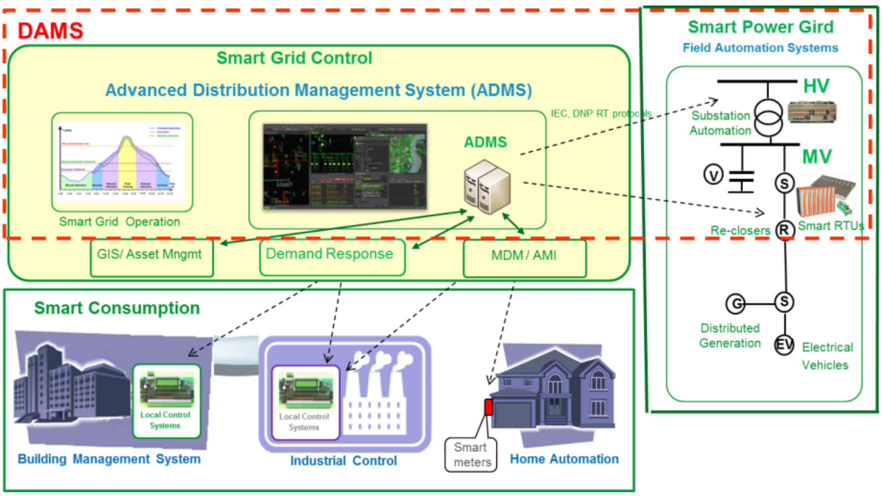

Figure 1
Smart Grid Solutions

Implementation of ADMS and Field automation solutions together can be referred as Distribution Automation Management System (DAMS). DAMS should reach various objectives, as advanced monitoring and control of distribution network; optimization and efficiency of network operation; reduction of power losses; reduction of power outage time, reduction of maintenance costs; efficient utilization of existing distribution facilities; postponement of investments; improvement of power quality, improvement of customer services; reduction of operation costs and increase of revenue. DAMS should provide advanced tools for dynamic visualization, monitoring and control of electricity distribution network, as well as smart applications for operation analysis, planning and optimization. The system should be built on open standards and integrated with other IT systems in a Utility, to enable optimal network operation, decision making and design.

Smart grid efficiency is analysed in many research papers [1-7]. The key performance indicators related to smart grid efficiency are presented in [5], using the fuzzy analytic hierarchy process for the determination of overall smart grid efficiency. The analysis shows that the dominant performances of the optimal smart grid project are efficiency, security and quality of supply. Evolutionary computation is applied in optimization algorithms [6], used for smart power grid control and based on genetic algorithms, neural networks, heuristic algorithms and fuzzy methodologies [5, 6, and 7].

In this paper, the performance analysis of DAMS solution is presented, based on the main benefits in increasing efficiency, security and quality of supply. The operation benefits are evaluated in the second section of the paper, based on the sample of a real power distribution grid. The typical cost of DAMS implementation and operation cost during the lifetime of the system are evaluated in the third section. In the fourth section, the performance analysis is conducted considering the lifetime of the system, to manifest the profitability of the solution. Consequently, conclusion and references are provided.

2 Benefits of DAMS Implementation

Distribution Automation Management System (DAMS) is considered as implementation of ADMS and Field automation solutions together (Figure 1). In this section, DAMS benefits are analyzed and evaluated [4]. A sample of one real distribution network system (DNS) is used for the evaluation of benefits and costs. DNS is supplied by one Primary Substation (PSS 110/35 kV) and four Distribution Primary Substations (DPS 35/10 kV). DNS supplies 25,000 consumers (meters), over 350 km of 10 kV medium voltage (MV) network, by 40 MV feeders and 360 Secondary Substations (DSS 10/0,4 kV), as presented in Figure 2. DNS annual peak load is 50 MW. The annual injected electrical energy (AIEE) into DNS is approx. 200 GWh/year, with a commercial value of approx. 7,500,000 $/year (assuming wholesale price in range 35–40 $/MWh). The DNS total power losses are 10% (technical and non-technical losses).

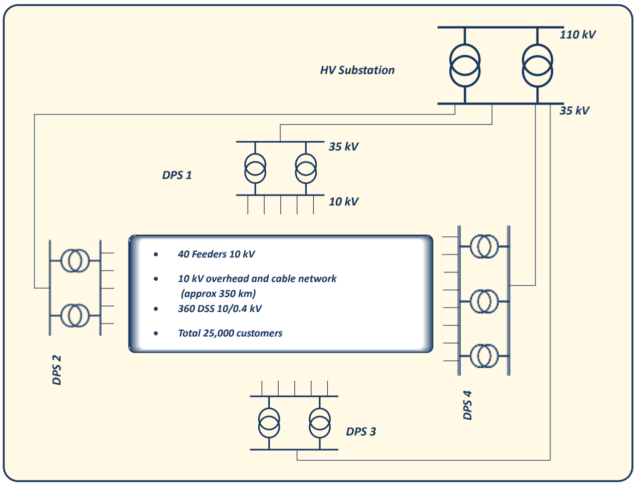

Figure 1
The example of a real Distribution Network

Implementation of DAMS should bring benefits in reduction of power losses; reduction of operation costs (reduced maintenance, outage time and non-supplied energy); reduction of network construction costs (improved utilization of facilities and postponement of investment) and in improving power quality. Such benefits are analyzed and evaluated in the following sections.

2.1. Reduction of Power Losses

Power losses are reported as the difference of the energy measured on entry points of the network and energy measured on consumption (customers) points, in one considered time period (typically one year). Technical power losses are related to energization of the network and power flow, while non-technical losses to problems with measurement and energy theft. Power losses are direct commercial loss to any RPC, since they have to be compensated by additional purchase of energy, as well as they contribute to pollution of environment. Therefore, there is always a high interest for reduction of losses and contribution of DAMS is presented in this section.

2.1.1. Optimal Feeder Reconfiguration

Power flow calculation [8] is based on the real-time state estimation and load profiles, providing real-time calculation of network operation state, for all transformers, feeders and laterals. Normally, distribution network is operated radially without loops, and if a feeder has connection to other feeders, the connecting switch would be normally open. The normally open switches (NOS) are providing possibility for restoration of supply in case of incidents. In large distribution networks with hundreds of feeders, there are hundreds of NOS, which may be subject of optimization to reach certain objective (minimum power losses, improved voltages, reduced overloads, etc.). The optimization approach in DAMS function "Optimal Feeder Reconfiguration" (OFR) provides such a solution [9 - 12], based on optimization algorithm where all switches are closed and then opened with minimal current deviation, but using network model with only resistances for power lines [9]. If results are applied in a real network operation, experience is showing up to 20% reduction of technical (peak) power losses in the MV network, with insignificant costs of changing NOS locations. Since MV losses are approximately 30% of total (peak) power losses (including HV, MV, LV network and transformers), and since energy losses are lower due to variation of load in time, the reduction of total energy losses would be in the range of 4-5%, which is confirmed in field results [13]. The reduction of energy injection in distribution network would be in the range of 0,4–0,5 % AIEE, considering typical energy losses, and reduction of energy that RPC has to purchase 4–5%.

2.1.2. Volt/Var Control

DAMS function "Voltage/Var control" (VVC) provides optimization of voltages and reactive power flow in distribution network in a real time state [14-16], keeping voltages inside technical constraints, but reaching optimization objective. It calculates the "optimal" setting of the voltage regulation devices (on-load tap changers) and capacitor banks, according to selected objectives (minimal power losses, voltage deviation, power demand, and others). On the basis of areas whose voltages are influenced by these control devices and their action speeds, the voltage control problem is decomposed in space and time [15]. The space decomposition enables a solution of the distribution voltage control problem for the medium voltage network of each supply transformer (substation) separately. As well, the time decomposition enables a solution in the operation planning mode and the real time mode separately. The voltage control is each time stated as a constrained optimization problem. The network voltage profile quality is quantified by the damage (inconvenience) that electric consumers sustain due to steady state voltage deviations. Therefore, this damage is used as the optimization objective.

In case of minimal power losses objective, test results are showing 10% additional reduction of MV network power losses in coordination with OFR. The cumulative effect of VVC and OFR is providing reduction of AIEE up to 0,5%.

2.1.3. Reduction of Non-Technical Losses

DAMS Energy Audit application enables archiving energy injection (recorded by meters) and technical losses (calculated) in MV feeders and MV/LV transformers, so that energy injection on the Low Voltage (LV) side is established, if not measured by specific meters. Technical losses in LV network can be calculated by DAMS applications, and then using billing data of LV customers "non-technical" losses can be allocated (theft, bad meters). Now, distribution transformers areas can be ranked according to the level of non-technical losses, and field crews sent to critical locations for control [17]. After reducing theft or metering failures, the injection of energy will be also reduced. The field results are showing reduction of non-technical energy losses minimum 0.5% of AIEE.

2.1.4. Total Reduction of Losses

In total, DAMS can contribute to 5–10% reduction of energy losses in distribution network, or 0.5 to 1% of AIEE.

In case of DNS (200 GWh energy injection), saving would be 1 to 2 GWh/year, or 35,000–75,000 $/year (using average wholesale price of 35–40 $/MWh), and divided by 25,000 customers (el.meters), is averaging **1.5-3** $/meter/year.

2.2. Reduction of Network Operation Costs

Network automation and DAMS is recently under implementation in many RPCs. Fault (outage) management is executed mostly manually with field crews, when a procedure may take several hours and customers along the feeder would suffer a long outage. The dispatcher has limited information about the network operational state. He faces the risk of making wrong decisions and extended outages, relying only on his experience, without any smart tools for decision support.

2.2.1. Direct Cost of Fault Management

DNS is having up to 150 MV feeder faults/year. In DNS without automation, the average duration of fault is approx. 2 hours, affecting 1000 customers or 1 MW of load, giving in average of 2 MWh of non-supplied energy per fault, or a total of 300 MWh energy of non-supplied energy per year (ENS). If the price of "distribution service" is approximately 4 c$/kWh (price that RPC is charging for services), then the lost revenue would be 12,000 $/year.

Additionally, due to frequent use of switching equipment in DNS with manual fault management, at least one circuit breaker would have to be replaced per year, because of the 300 switches on fault current (2–3 switches per fault), which has a cost of a minimum of 6,000 $/year. Similarly, at least 4 load switches should be replaced, because of 800 switches on load (5–6 switches per fault), which has a cost of a minimum of 16,000 $/year. The cost of field crew engagement for 800 switches in field (25 $/switch) is approx. 20,000 $/year.

The total direct cost of fault management in DNS, without DAMS, would be approx. 54,000 $/year.

2.2.2. Outage Compensation Cost

The liberalization of the electrical sector introduces compensations paid by RPC to customers because of outages, or exposure of RPC to penalties defined by the regulator. Regulation models are different in countries, but in many cases RPCs are exposed to additional cost for compensation of damages to customers, for example, RPCs in Holland pay compensation of 35$ to every customer for outages longer than 4 h (Netherlands Authority for Consumers and Markets). In some countries revenue and tariffs of RPC are exposed to penalties related to operation performance, for example, each hour lost cost RPC in UK approx. 20$/customer (Ofgem – UK Office of Gas and Electricity Market).

Exposure to penalties or outage compensation cost can be estimated, as ENS multiplied with the average service price and a multiplication factor, which can be in the range from 0 (no exposure) to 20 times (full exposure). If ENS in DNS is 300 MWh/year, then outage compensation costs in case of DNS would be in the range from 0 to 240,000 $/year. In most cases, exposure is not high, or outage compensation costs are paid rarely, so on average the ENS price should be multiplied approx. 5 times, and the average price of ENS can be assumed as 20 c$/kW. Thus, the average outage compensation cost in case of DNS would be 60,000 $/year.

2.2.3. Implementation of DAMS

Deployment of DAMS (ADMS and field automation) would significantly improve the fault management, reduce outage time, and reduce direct and compensation costs paid by RPC [4]. DAMS would require remote control of all HV Substation, remote control of certain number of MV load-switches (approx. 20%), implementation of fault detectors and central smart management system (ADMS). The fault would be located analytically, using algorithm for fault location, isolation and restoration [18], without need for many switching of equipment. The minimal necessary switching will be done remotely, and average outage time would be significantly reduced, almost 5 times, down to 15 – 20 minutes. In DNS, ENS would reduce to 60 MWh/year.

The lost revenue would decrease to 2,400 $/year because of ENS reduction. The maintenance cost would be significantly reduced: one breaker failure in two years (3,000 $/year) instead each year, one switch failure per year (4,000 $/year) instead of four failures, less crew engagement (200 switching, or 5,000 $/year). Thus, the total direct cost would decrease to 14,400 $/year. Compensation cost would decrease to 12,000 $/year (60 MWh x 20 c$/kWh). Therefore, the total saving after deployment of DAMS, would be 88,000 $/year, which equals 1.25% AIEE or 3,5 $/meter. However, if exposure to penalties is considered in the higher range, then savings would be even higher.

DAMS can contribute to reduction of maintenance and network operation costs and provide savings of 1.25% AIEE, or **3,5 $/meter/year**.

2.3. Reduction of Network Construction and Development Costs

The network study and planning tools enable efficient utilization of existing distribution facilities with up to 20% postponement of investments in network constructions.

The normal construction of distribution facilities, due to new customer connections or resolving of power overloads, increases the number of distribution transformers on average 1% annually, as well as the length of MV power lines by 0.5%. In DNS, on average 4 new DSS and 2 kilometers of MV power lines should be built every year (4 x 30,000 + 2 x 90,000 = 300,000 $/year investments); however, with DAMS, investment would be postponed and reduced to 3 DSS and 1.6 km of MV power lines (234,000 $), giving a savings of approximately $66,000 annually.

The more efficient resolution of large outages using DAMS, by more efficient utilization of reserves in adjacent MV network, would postpone construction of new primary substations. *ADMS Large Area Restoration* functionality enables the efficient resolution of large HV supply transformer outages. In DNS, one DPS should be normally built every 10 years (1,000,000 $ investment); however investment can be postponed and save 50,000–80,000 $ per year in less depreciation or interest.

In total, reduction of network construction costs in DNS case would be in range 116,000-146,000 $/year, or 1.5-2.0% of AIEE. Therefore, DAMS can contribute to reduction of construction costs and provide savings of 1.5-2% AIEE, or **4,5-6 $/meter/year**.

2.4. Improved Power Quality

DAMS Voltage/Var Optimization application provides real-time regulation of on-load tap-changers on HV/MV transformers (PSS and PDS) and seasonal setting of off-load tap-changers on MV/LV transformers in DSS. Voltages are maintained within technical limits to provide power quality and minimize damages to customers due to voltage deviations. Additionally, voltages are maintained in optimal profile in dependence of the network operation state: in regular state reducing active and reactive losses; in emergency state reducing peak load; in extra energy state increasing demand. Guaranteed power quality can be provided for special sensitive customers, as well as electricity sales can be impacted by changes of voltage level according to electricity market prices.

Testing results are showing savings of 0.5-1 % of AIEE, or **1,5–3 $/meter/year**.

2.5. Total Benefits

The total benefits of DAMS implementation, as well as DAMS benefits per type, are presented in the Table 1.

Table 1
DAMS total annual benefits

Benefit type	DAMS tool	Saving/year (% of AIEE*)	Saving/year ($/meter/year)
Reduction of energy losses	Optimal Feeder Reconfiguration, Volt/Var Control	0.5 - 1%	1.5 - 3
Reduction of network operation costs	Fault Management automation	1.25%	3.5
Reduction of network construction costs	Network construction planning and load forecast	1.5 - 2%	4.5 - 6
Improved power quality	Volt/Var Optimization	0.5 - 1%	1.5 - 3
Total Benefit		3.75 – 5.25%	11 – 15.5
Average Benefit		**4.6 %**	**14**
* Saving in % of the Annual Injected Electrical Energy (AIEE) into the distribution network			

The total benefits of DAMS implementation, as discussed in this section, should provide aggregated annual savings of 4.6% of AIEE, or **14 $/meter/year**.

3 Cost of DAMS Implementation

The costs of DAMS implementation encompass three areas [4]:

- *DAMS Software and IT hardware,* deployed in Main and Back-up data centres and Control Rooms (Dispatching Centres) of RPC, including costs of software licenses, engineering (design, configuration, data migration), delivery, testing, training, commissioning, support and maintenance.

- *Substation and Feeder automation,* including intelligent local master systems or remote terminal units (RTU) for local signal acquisition, processing and conversion, implemented in substations and overhead lines (pole mounted switches), with costs of equipment, delivery, commissioning, testing and maintenance.
- *Communication system* (radio links, fibre optic, public providers), including costs of system design, licenses for radio frequencies, delivery of equipment, testing commissioning, maintenance, or cost of subscription on communication providers.

Distribution automation principles recommend remote control of all NOS, as well as a certain number of MV load switches (e.g. on a third or half of the feeder) and fault detectors, to be able to execute a fast supply restoration and reduce outage time. Additionally, all supplying primary HV Substations and larger MV switching points should be under remote control. More RTUs in network would bring better results, but would rapidly increase investment cost. Some of the DAMS functions may be used for deeper analysis and design of the optimal level of automation, keeping investment inside a limited budget. The minimum level of investment in case of DNS is presented in Table 2.

Some old power equipment should be replaced to be controlled by automation systems (e.g. replacement of old air-insulated load-breakers with gas insulated Ring Main Units or Pole Mounted Switches), but power equipment is typically another line of investments. Since automation cost is considered from scratch However, many RPCs has already invested in certain automation equipment, it is assumed that the value of the existing automation equipment equals investment cost in replacement of old power equipment.

According to results of DNS investment analysis (Table 2), it can be generalized that DAMS investment costs typically consist of:

- DAMS SW/IT investment costs, which are in the range 5-8 $/customer (meter), depending on the network size and functionalities included. Typically, average price per meter is higher for smaller projects and lower for large projects, making 20% of the total DAMS investment,
- Communication systems are in the range of 4-8 $/meter, making 20% of the total DAMS investment.
- Cost of automation equipment with installation costs, this is the largest part, making 60% of the total DAMS investment, and it is in the range of 20-25 $/customer (meter),

The total investment costs in DAMS, as discussed in this section, are in the range of 29–41 $/meter, and for further analysis the average value of **35 $/meter** will be used. It equals 12% of AIEE value.

Table 2
DNS automation investment cost

DNS automation cost (25,000 customers/meters)	Unit price ($)	No of units	Price for DNS ($)	Price per customer ($/meter)
DAMS Software and IT hardware	125,000 - 200,000	1	125,000 – 200,000	5 - 8
PDS automation, RTU, cabling and interfaces	40,000 - 50,000	4	160,000 – 200,000	20 - 25
DSS, RTU, cabling and interfaces	4,000 - 5,000	25	100,000 – 125,000	
PMS, pole mounted switches, RTU and interfaces	3,000 - 4,000	70	210,000 – 280,000	
Distribution switching yard, RTU and interfaces	10,000	3	30,000	
Communication system: Fibre Optic interfaces, or radio equipment, interfaces, antennas, etc.	1,000 – 2,000	100	100,000 – 200,000	4 - 8
Total DAMS automation cost of DNS			725,000 – 1,035,000	29 - 41
Average DAMS cost ($/meter)				**35**

4 Cost Benefit Analysis

The cost–benefit economic analysis will be made comparing average annual costs and benefits of DAMS project, as well as comparing the total cost of ownership and total benefits over the lifetime of DAMS system [19] – [20].

4.1 The Method of Annual Costs

Profitability and attractiveness of an investment can be evaluated with the method of annual cost. In this method, cost and benefits in one year of operation are compared, assuming that they are not changing over the lifetime of the system. This is not fully correct because the value of money is changing over time, but for quick and simplified analysis this method can be used, mostly to show approximate profitability.

The annual cost of DAMS system operation can be evaluated taking into account annual investment cost (depreciation), operating cost and financial cost:

- Depreciation (*d* %) is calculated in economics as inverse value of the system lifetime, where the system lifetime is presented in years and depreciation in percentages. Depreciation is percentage of initial investment cost (I_0), which RPC should spend each year on "renewal" of the assets, so that assets never lose value. If we assume the lifetime of DAMS as 10 years, then depreciation cost would be 10% of I_0.

- The operating and maintenance cost for using of the system (*m* %) are approximately 5% of I_0. Such cost typically include engagement of RPC's personnel, hardware and equipment maintenance, license subscriptions, etc.
- Financial cost (*int* %) includes average cost of capital, or interest in case of loan, taxes, etc., and they are in the range of 3-5% of I_0.

Thus, the annual cost of operating DAMS system ($C_{a,i}$) in year "*i*" can be expressed as in equations (1) and (2):

$$C_{a,i} = (d\% + m\% + \text{int}\,\%)\; I_0 \tag{1}$$

$$C_{a,i} = (10\% + 5\% + 5\%) I_0 = 20\;\%\; I_0 \tag{2}$$

If initial investment cost for DAMS implementation (I_0) is 35 \$/meter, according to section 3, then the annual cost of using DAMS is approx. 7 \$/meter/year.

The total annual benefit of DAMS operation ($B_{a,i}$) is calculated in chapter 2.5, resulting in 14 \$/meter/year.

Now, the annual profitability ($P_{a,i}$) of DAMS project is calculated as ratio of annual benefits ($B_{a,i}$) and costs ($C_{a,i}$), as expressed in equation (3):

$$P_{a,i} = \frac{B_{a,i}}{C_{a,i}} = \frac{14\,\$/meter}{7\,\$/meter} = 2 \tag{3}$$

Therefore, the method of annual cost is showing that DAMS projects have a very good profitability, because benefits will be twice higher then cost during each year of operation.

4.2 Discounting Method

The most accurate is the discounting method, which is considering the total cost over the lifetime of the system, or the total cost of ownership (TCO), comparing with the total benefits that system will provide over the lifetime or the total benefits of ownership (TBO).

Since the capital has to bring return over time, as discounting parameter is used "weighted average cost of capital" (*wacc%*). TCO can be expressed, as in equation (4):

$$C_{T,0} = TCO = \sum_{i=1}^{T} \frac{(d\% + m\% + \text{int}\,\%)_i\, I_0}{(1 + wacc\%)^i} \tag{4}$$

If we consider that annual costs are constant over time, then TCO can be expressed as in equation (5):

$$C_{T,0} = TCO = (d\% + m\% + \text{int}\,\%)I_0 \cdot \sum_{i=1}^{T} \frac{1}{(1+wacc\%)^i} \tag{5}$$

If discounting factor (*DF*) is introduced, and *wacc%* assumed 5%, then *DF* can be expressed as in equation (6):

$$DF = \sum_{i=1}^{T} \frac{1}{(1+wacc\%)^i} = \sum_{i=1}^{T} \frac{1}{(1+5\%)^i} = 7{,}72 \tag{6}$$

TCO can be expressed as in equation (7):

$$C_{T,0} = TCO = C_{a,i} \cdot DF = 20\%\, I_0 \cdot 7{,}72 = 1{,}54 \cdot I_0 \tag{7}$$

TCO of DAMS project, with the lifetime of 10 years, will be 1.54 times of initial investment, or 7,72 times of annual cost.

If I_0 is estimated on 35 $/meter (Table 2), then TCO of DAMS project during 10 years will be **54 $/meter**.

On the other side, TBO can be easily calculated in a similar way, equation (8):

$$B_{T,0} = TBO = B_{a,i} \cdot DF = B_{a,i} \cdot 7{,}72 \tag{8}$$

If annual benefit ($B_{a,i}$) is 14 $/meter/year (Table 1), then TBO of DAMS project, during lifetime of 10 years, will be **108 $/meter**.

The economic evaluation with discounting method is made using four typical economic parameters:

a) *Profitability* (*P*) – this economic factor describes the profitability of the project, using ratio of total benefits and costs during the project lifetime, as in equation (9):

$$P_{T,0} = \frac{TBO}{TCO} = \frac{108\,\$\,/\,meter\;/\,10\,years}{54\,\$\,/\,meter\;/\,10\,years} = 2 \tag{9}$$

DAMS projects are showing a high profitability, because benefits provided will be twice higher then all costs during the lifetime of the project.

b) *Payback* – this economic factor describes the time necessary for the return of investment, and the year when project starts to provide profit, as expressed in equation (10):

$$Payback = \frac{T}{P_{T,0}} = \frac{10\ _{years}}{2} = 5\ years \tag{10}$$

DAMS projects are showing a good payback time of 5 years, and providing the profit in the following 5 years.

c) *Return on Investment* (*ROI*) **–** this economic factor describes the added value over invested amount, that project will bring during the lifetime, as expressed in equation (11):

$$ROI = \frac{TBO - TCO}{TCO} 100 = \frac{108 - 54}{54} 100 = 100\ \% \tag{11}$$

DAMS will create added value of 100%, which means that on each dollar spent, over two dollars will return.

d) *Internal Rate of Return* (*IRR*) – this economic factor describes how much the investment is attractive compared with the average cost of the capital. It is calculated as the discounting factor by which the *Net Present Value* (*NPV*) would equal to zero, or investment wouldn't bring any profit over lifetime, as expressed in equation (12):

$$NPV = -I_0 + \sum_{i=1}^{10} \frac{B_{a,i} - C_{a,i}}{(1 + IRR)^i} = 0 \tag{12}$$

NPV is the total profit over the lifetime discounted on the present date and then reduced by initial investment. If IRR is higher than average cost of capital, then the investment is attractive. In DAMS case, IRR is 15%, which is three times higher than average cost of capital (5%), showing high attractiveness of DAMS investment.

Economic analysis of DAMS projects is showing a high business attractiveness in any of four economic parameters: they are more than two times profitable, payback is half of the lifetime, return on investment is two times, and internal rate of return is very high.

4.3 Sensitivity Analysis

Sensitivity analysis was made to explore the impact of existing distribution automation levels on profitability of DAMS projects. Three scenarios were created:

a) Scenario A – *Typical state (TS)*: This is a typical situation in RPCs nowadays with small level of distribution automation (10-20% of the full automation level). This situation was considered in analysis of benefits in section 2 and costs in section 3. DAMS investment cost ($I_{0,TS}$) to reach full automation would be 35 \$/meter, while annual benefits 14 \$/meter/year (4,6% AIEE).

b) Scenario B – *Advanced state (AS)*: There are some advanced RPCs which recently invested more in automation, and already reached 30-40% of the full automation level (e.g. North America, North Europe). In this case, investment cost I_0 would be lower than in Scenario A. If assumed that 2/3 of the full I_0 would be necessary, then ($I_{0,AS}$) in this case would be 22 \$/meter. Also, benefits would be slightly lower, since certain benefits of outage reduction would already have been reached. If half of outage reduction benefits is already reached, then annual benefits would be in a range of 13 \$/meter/year (4.3% AIEE).

c) Scenario C – *Full automation (FA):* There are a few very advanced RPCs which already reached the full automation (e.g. Japan, Singapore, Hong Kong, New York, etc.). In this case, further investment in automation is not necessary anymore, but it is necessary in DAMS system deployment (software and computer equipment). According to Table 2, only DAMS investment ($I_{0,FA}$) would be 8 \$/meter. Benefits would also be lower, since fault management automation was already reached, but other benefit (e.g. power losses reduction, etc.) would produce at least 12 \$/meter/year (4% AIEE).

The economic evaluation (discounting method) was made with scenarios A, B and C, using equations for TCO (7) and TBO (8), and DNS with 25,000 meters. The four typical economic parameters are calculated using equations 9–12, and results are presented in the Table 3.

Table 3

DAMS profitability with different automation levels

Scenario (autom.level)	TCO (\$)	TBO (\$)	P	ROI	IRR	PbT (years)
A – Typical state	1,347,500	2,702,000	2.00	100%	15%	5
B – Advanced state	847,000	2,509,000	2.96	196%	37%	3.38
C – Full automation	308,000	2,316,000	7.52	652%	130%	1.33

The sensitivity of four economic parameters on automation levels is presented graphically in Figures 3-6.

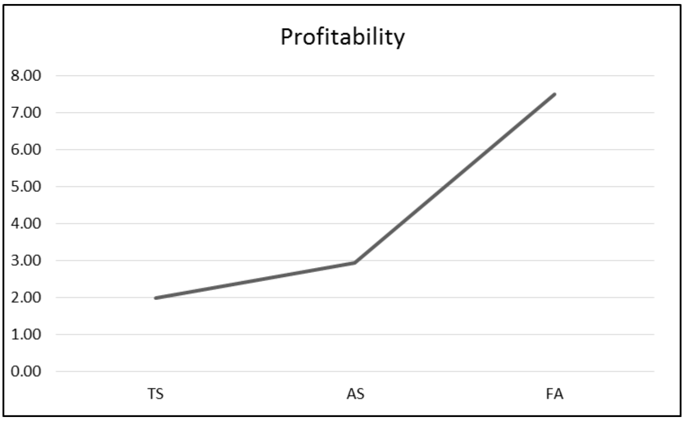

Figure 3
DAMS Profitability in different automation levels

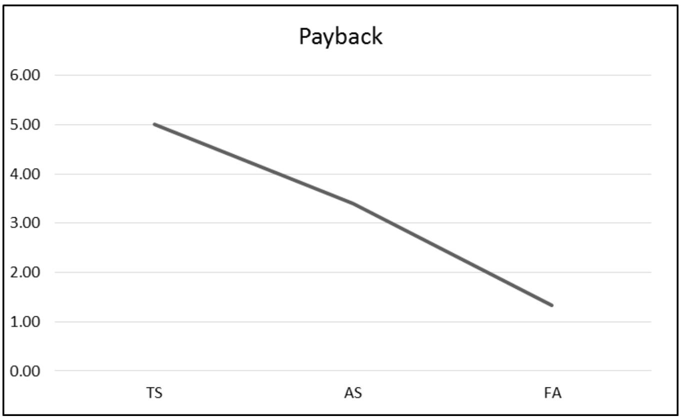

Figure 4
DAMS Payback time in different automation levels

The sensitivity analysis is clearly showing significant impact of automation level on profitability of DAMS projects. If existing automation level of the distribution network is higher, DAMS costs and TCO will be significantly lower because automation cost are highest. However, since most benefits are coming from software optimization features (reduction of power losses, postponement of constructions, power quality) TBO will keep high values. Consequently, all economic parameters will be much better. Profitability would increase by 3 times in case of advanced RPCs and up to 7 times in case of the full automation. Payback time would reduce over 3 years in case of advanced RPCs and down to 1 year in the full automation case. IRR and ROI would show much higher values creating high attractiveness of investments into DAMS.

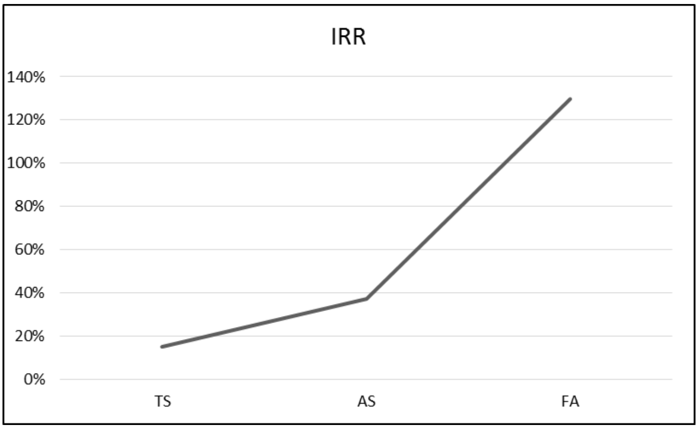

Figure 5
DAMS IRR in different automation levels

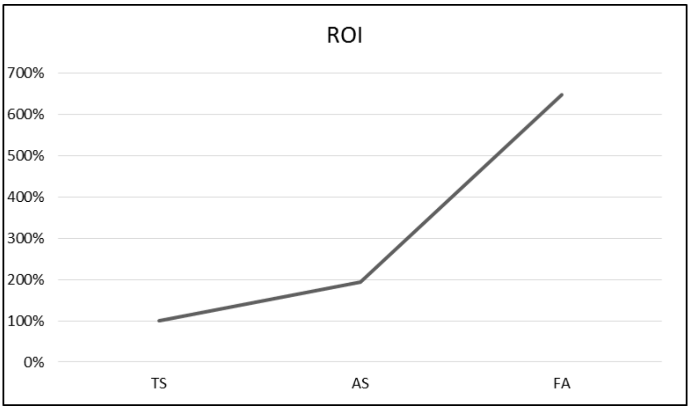

Figure 6
DAMS ROI in different automation levels

Conclusions

Investments in DAMS projects should be very profitable. The results of economic evaluation and sensitivity analysis are showing very good economic performance:

- *Good Profitability:* in most of regulated power distribution companies (RPCs) with small automation level nowadays, benefits would be *two times* higher than costs over the lifetime of a project. In RPCs with advanced automation level, profitability would be over *three times*. In case of the full automation, when investment is only in DAMS software and computer equipment, profitability would be even as much as *seven times*.

- *Short Payback time:* investment would return in 5 years in the low automation case, but in 3 years in the advanced case, or even in 1 year in the full automation case, showing a longer time for providing the profit.
- *High Return on Investment:* even in RPCs with small automation return on investment would be 100%, which means that on each dollar invested, two dollars will return. In advanced and fully automated RPCs, return would be even much higher, showing a high attractiveness of investment.
- *Attractive Internal Rate of Return:* in RPCs with small automation IRR (15%) is three times higher than average cost of capital, showing a very good attractiveness of investment. In advanced and full automated RPCs IRR is much higher, showing even higher attractiveness of investments in DAMS.

Finally, since not all DAMS benefits could be financially evaluated (e.g. improving safety on work, reducing damages, improving customer satisfaction, etc.), attractiveness of DAMS investment may be even higher.

References

[1] D. Molzahn, F. Dorfler, H. Sandberg: A Survey of Distributed Optimization and Control Algorithms for Electric Power Systems, IEEE Transactions on Smart Grid, Volume 8, issue 6, November 2017, pp. 2941-2962

[2] N. Katic: Profitability of Smart Grid Solutions Applied in Power Grid, Thermal Science, Vol. 20, Suppl. 2, 2016, pp. S371-S382

[3] S. Mohtashami, D. Pudjianto, G. Strbac: Strategic Distribution Network Planning with Smart Grid technologies, IEEE Transactions on Smart Grid, Volume 8, Issue 6, November 2017, pp. 2656-2664

[4] N. Katic: Benefits of Smart Grid Solutions in Open Electricity Market, Acta Polytechnica Hungarica, Vol. 10, No. 2, 2013, pp. 49-68

[5] A. Janjic, S. Savic, G. Janackovic, M. Stankovic, L. Velimirovic: Multi-Criteria Assessment of the Smart Grid Efficiency Using the Fuzzy Analytic Hierarchy Process, Facta Universitatis, Series: Electronics and Energetics, Vol. 29, No. 4, 2016, pp. 631-646

[6] V. Oduguwa, A. Tiwari, R. Roy: Evolutionary Computing in Manufacturing Industry: an Overview of Recent Applications, Applied Soft Computing, Vol. 5, No. 3, 2005, pp. 281-299

[7] A. Urmos, Z. Farkas, M. Farkas, T. Sandor, L. T. Kocsy, A. Nemcsics: Application of Self-Organizing Maps for Technological Support of Droplet Epitaxy, Acta Polytechnica Hungarica, Vol. 14, No. 4, 2017, pp. 207-224

[8] S. Cheng, D. Shirmohammadi: A Three-Phase Power Flow Method for Real-Time Distribution System Analysis; IEEE Trans. on Power System, Vol. 10, No. 2, May 1995, pp. 671-679

[9] D. Shirmohammadi, H. W. Wong: Reconfiguration of Electric Distribution Networks for Resistive Line Losses. IEEE Trans. on Power System 1989; Vol. 4, No. 2

[10] M. E. Baran, F. F. Wu: Network Reconfiguration in Distribution Systems for Loss Reduction and Load Balancing, IEEE Trans. On Power Delivery, Vol. 4, No. 2, April 1989

[11] I. Roytelman, V. Melnik, S. S. H. Lee, R. L. Lugtu: Multi-Objective Feeder Reconfiguration by Distribution Management System, IEEE Trans. on Power System, Vol. 11, No. 2, May 1996, pp. 661-667

[12] J. Cebrian, S. Rahman, N. Kagan: Restoration in Distribution Systems to Reduce Financial Losses Related to Process Trips, IEEE Transactions on Smart Grid, Volume 8, Issue 1, January 2017, pp. 219-227

[13] G. di Lembo, P. Petroni, Ch. Noce: Reduction of Power Losses and CO2 Emission: Accurate Network Data to Obtain Good Performances of DMS Systems, CIRED 20th Conference Prague, June 8-11, 2009, Prague, Czech Republic

[14] I. Roytelman, B. K. Wee, R. L. Lugtu: Volt/Var Control for Modern Distribution Management System, IEEE Trans. on Power System, Vol. 10, No. 3, August 1995, pp. 1454-1460

[15] V. Strezoski, N. Katic, D. Janjic: Voltage Control Integrated in Distribution Management Systems, Electric Power Systems Research, No. 60, 2001, pp. 85-97

[16] A. Hamouda, K. Zehar: Improvement of the Power Transmission of Distribution Feeders by Fixed Capacitor Banks, Acta Polytechnica Hungarica, Vol. 4, No. 2, 2007, pp. 47-62

[17] N. Katic, J. Katic: Reduction of Non-technical Power Losses as a Significant Improvement of Utilities' Operation Efficiency, SEEEI 2016, Electricity International Convention, Session TAM X, published in electronic form, Eilat, Israel, December 6-9, 2016

[18] A. Zidan and all: Fault Detection, Isolation and Service Restoration in Distribution Systems: State-of-The-Art and Future Trends, IEEE Transactions on Smart Grid, Volume 8, Issue 5, September 2017, pp. 2170-2185

[19] A. A. Sallam, O. P. Malik: Electric Distribution Systems, John Wiley & Sons, New Jersey, 2011

[20] D. Kirschen, G. Strbac: Power System Economics, John Wiley & Sons, England, 2004