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Published in:
IEEE 81st Vehicular Technology Conference (VTC Spring), 2015

DOI (link to publication from Publisher):
10.1109/VTCSpring.2015.7145698

Publication date:
2015

Document Version
Early version, also known as pre-print

Analysis of Information Quality in event triggered Smart Grid Control

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I. Abstract

The integration of renewable energy sources into the power grid requires added control intelligence which imposes new communication requirements onto the future power grid. Since large scale implementation of new communication infrastructure is infeasible, we consider methods of increasing dependability of existing networks. We develop models for network delays and information dynamics, and uses these to model information quality for three given information access schemes in an event triggered control scenario. We analyse the impact of model parameters, and show how optimal choice of information access scheme depends on network conditions as well as trade-offs between information quality, network resources and control reactivity.

II. Introduction

Today energy is mainly produced using non-renewable energy sources [1]. However, it is desired to rely more and more on several types of renewable energy sources. Wind turbines and solar panels are gaining popularity in households, meaning that energy production is changing from a more centralized system to a highly distributed system. In addition, the energy production is moving from high voltage(HV) and medium voltage(MV) power grids to the low voltage(LV) power grid. To enable the power grid to handle the requirements of the highly dynamic energy production from renewable energy sources at the low voltage level, it must be possible for the distribution grid to have better control of grid assets.

To facilitate added control intelligence in smart grid systems, a communication infrastructure must be in place as well as functionality to allow grid asset control, which for the LV grid is non-existing. Since the assets are highly distributed, dependable communication is required to allow proper grid operation, however, this is not without challenges since several trade-offs must be made [2].

Since large scale implementation of new communication infrastructure is not economically feasible, existing communication infrastructures are considered. However, existing communication infrastructures must be wide spread enough to cover the entire power grid, and have to be shared with the current users. This causes heterogeneous network behaviour, which must be considered when designing a system that must provide high dependability like power grid systems.

This problem can be tackled from several angles: [3] investigates in numerous articles how heterogeneous networks can be taken into account when designing control systems. Similarly [4] shows how control loop intervals can be changed dynamically depending on communication network quality. In this paper we investigate the problem from a network perspective by attempting to increase dependability of the communication network in a smart grid low voltage control scenario. [5] develops a middleware solution for adapting control set-points to counter poor network performance. However, this solution is limited to a specific controller type. In this paper we propose a middleware solution that can be generalized to a wider set of controllers by extending the work of [6] and adapt information access strategies based on the probability of the controller using incorrect information. The impact of the mismatch probability (mmPr) on communication network buffers is investigated for different access strategies in a context management system in [7].

In this paper we present models for the mmPr in three different information access schemes in a smart grid low voltage control scenario, based on developed information and network Quality of Service models. We evaluate the models and conclude on the trade-offs put forth by the different access schemes.

We start by defining the considered control scenario in section III, where we also define communication patterns for the different information access schemes. In section IV we present the used information and network models, as well as the developed mmPr models. The resulting model dynamics are shown and discussed in section V, and finally we draw conclusions in section VI.

III. Scenario description

We are considering an event driven voltage controller controlling several assets in a low voltage power grid. The controller is event driven, meaning that the assets runs on their own until a voltage has exceeded its threshold as illustrated in Figure 1. Here, two voltage bands are illustrated, a hard limit defined by the grid codes and a soft threshold defined by the controller to ensure the hard limit is never reached. When the voltage threshold is exceeded at a point in the grid, the controller must handle the problem locally (see Figure 2). The voltage is measured at sensors in the assets and an event will be detected by the assets physically close to the point of the event.

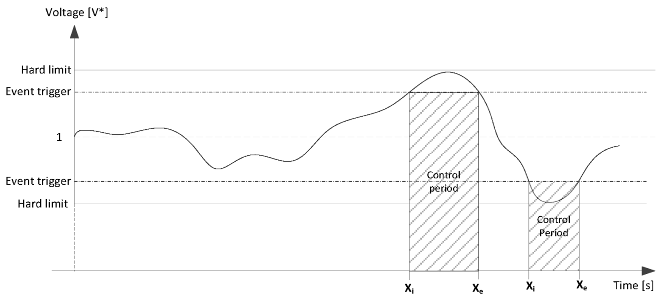

Figure 1. Definition of the events in the grid that triggers a (series of) control action.

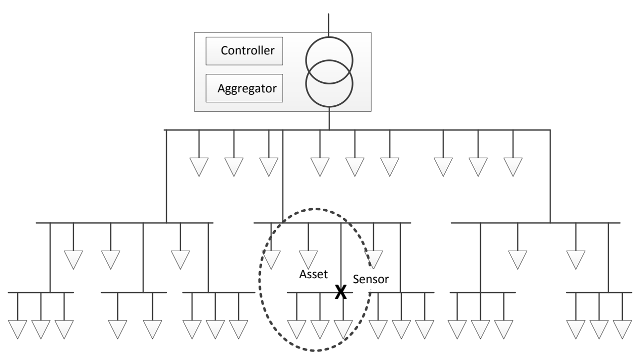

Figure 2. An example of an electrical low voltage grid.

The group of assets handling the event and the group of assets detecting is not necessarily the same, but can, for simplicity, be assumed to be. This means that for a single event only the small group of assets is affected and all other can be disregarded. Group sizes will be in the order of 5-10 assets, compared to the 100-200 assets in a typical low voltage grid. When an event happens, the following must happen:

1) The controller must become aware of the event.
2) The controller will calculate set points based on the assets' flexibility.
3) The control set points must be distributed to the assets.

In this scenario we consider the response time (t_{response}), the time from a voltage event happens, until new set points has been distributed, and the mismatching time (t_{mmPr}), the time from flexibility information is read at the asset, until the set points has been distributed. To calculate new set points when an event is detected, the controller must have information about the available flexibility of the assets. The controller does not necessarily need flexibility information from all affected assets and will only ask the relevant assets for information before determining new set points for the assets. This information flow is illustrated on Figure 3; here the total response time of the controller is shown (t_{response}), as well as the time in which a change in flexibility information could lead to the controller determining new set points based on outdated information (t_{mmPr}). This scheme for accessing flexibility information will be denoted the reactive scheme. For the message sequence diagrams the following notation is used: u_i is the delay experienced by the i'th message sent to the controller; d_i is the delay experienced by the i'th message sent from the controller; F_i denotes the time at which the i'th flexibility information chance occurs; and U_i is the time at which the i'th flexibility information is sent from the asset.

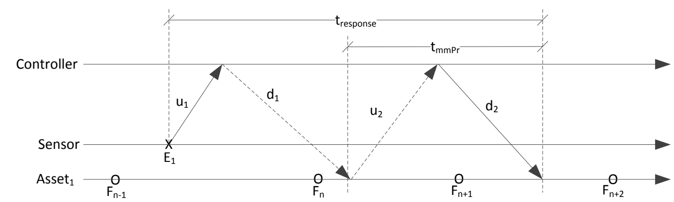

Figure 3. Message sequence diagram showing the information flow when a voltage threshold is exceeded using the reactive approach to access flexibility information.

Alternatively the flexibility information could be accessed by an information access scheme independent on voltage events. Figure 4 shows this for flexibility updates sent to the controller using a periodic scheme. For mathematical simplicity these flexibility updates will be sent according to a Poisson process. As seen on Figure 4, this scheme will decrease the controllers response time, but increase the time where changes in the flexibility can lead to information mismatch. This access scheme will be denoted the proactive periodical scheme.

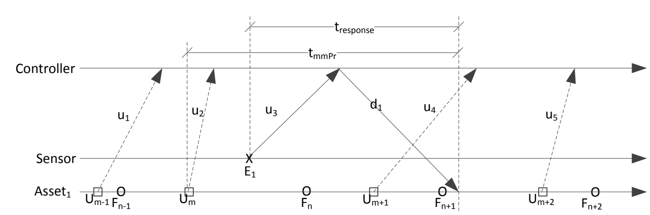

Figure 4. Message sequence diagram showing information flow when flexibility information is accessed periodically independent of voltage events.

Additionally we consider a proactive scheme where flexibility information is sent from the asset using an event driven process, i.e. the asset sends flexibility information whenever it changes. This access scheme is shown in Figure 5.

In addition to the different information mismatch times and response times, the three schemes uses different network resources. With an average rate of voltage events of λ_V, an average rate of flexibility events λ_F and an average rate of updates for the periodical scheme of τ, the traffic from each scheme can be described as the average number of packets sent per time interval:

$$R_{\text{rea}} = 4 \cdot \lambda_V \tag{1}$$
$$R_{\text{per}} = \tau + 2 \cdot \lambda_V \tag{2}$$
$$R_{\text{ev}} = \lambda_F + 2 \cdot \lambda_V \tag{3}$$

From these it is seen that if voltage events are very common compared to the others, the reactive scheme will cause higher network loads, whereas if τ or λ_F are significantly higher than λ_V, the reactive scheme will be more efficient with respect to network resources. Ultimately this will come down to a trade-off between network resources and control performance. Control performance is, however, delimited from this paper.

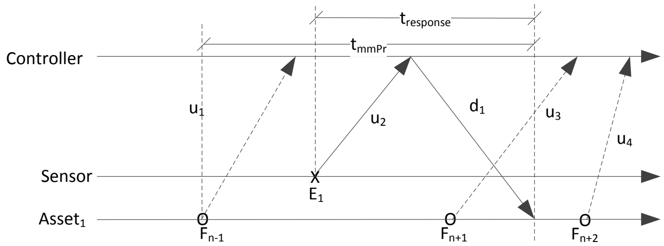

Figure 5. Message sequence diagram showing information flow when flexibility information is accessed using the proactive event driven process.

IV. Mismatch probability modelling

In this paper we investigate how to determine optimal information access schemes using mmPr as a scalar performance metric. The mmPr will be modelled mathematically for the reactive and proactive periodical schemes, whereas simulations will be used to evaluate the proactive event driven scheme. Simulations are used for this since dependability between the information upload times and flexibility events results in high mathematical complexity for this model. For the models insignificant processing delays compared to the network delays are assumed, but processing delays can be incorporated into the network delays by convolution. It is also assumed that the assets and the sensors are on the same network and, therefore, share the same independent network delay distributions. It is also assumed that updates happens with time intervals according to a Poisson process for the periodical scheme. Since access schemes can be chosen individually for each asset, only a single asset will be considered for the the mmPr models. In addition to the mmPr, we also consider the response time of the controller given by its density function f_{resp}. Although a mathematical model for the mmPr in the proactive event driven scheme was not found, the response time distribution for this scheme was determined.

Generally we define the mmPr as:

$$Pr(mm) = \int_0^\infty Pr(mm|t) f_{mmPr}(t) dt \tag{4}$$

where, $Pr(mm|t)$ is the probability that the offered flexibility has decreased during the time t and $f_{\text{mmPr}}(t)$ is the probability density function of the mismatching time.

To construct the mismatching time density we consider two density functions: $f_u(t)$ is the distribution of network delay for the upload of flexibility information and voltage events, and can be chosen as any appropriate distribution; $f_d(t)$ is the distribution of network delay for the download of set points, and can also be chosen as any appropriate distribution. Using these and an update rate of τ for the periodical scheme, f_{mmPr} and f_{resp} can be constructed for the different access schemes:

$$f_{\text{mmPr,rea}} = (f_u * f_d)(t) \tag{5}$$
$$f_{\text{resp,rea}} = (f_u * f_u * f_d * f_d)(t) \tag{6}$$
$$f_{\text{mmPr,per}} = (f_d * f_w)(t) \tag{7}$$
$$f_{\text{resp,per}} = (f_u * f_d)(t) \tag{8}$$
$$f_{\text{resp,ev}} = (f_u * f_d)(t) \tag{9}$$

Here,

$$f_w = \exp(-\tau \int_0^t F_u(v)\mathrm{d}v)\tau F_u(t) \tag{10}$$

A. Information modelling

To be able to define $Pr(mm|t)$, a suitable model for the flexibility information must be defined. We model the flexibility information using a Markov birth/death chain with the states representing the amount of flexibility offered by the asset, shown on Figure 6. In this model, we define an information mismatch as the system being in a state offering less flexibility when the set points have been distributed than it did when the information was read (i.e. $i > j$ for $S(t) = S_i$ and $S(t + \Delta T) = S_j$ for some $\Delta T > 0$).

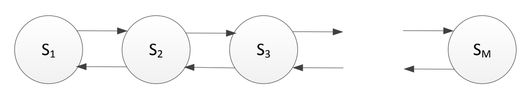

Figure 6. Markov chain model of flexibility.

We define the Markov chain using the generator matrix $\mathbf{Q}$ (as shown in Equation 11 for a Markov chain of M states), and calculate the stationary probabilities $\boldsymbol{\pi}$ from the constraints shown in equation 12 and 13. We also define $p_{ij}(t)$ as the probability of being in state j at time t given that the system where in state i at time 0. This can be calculated from the generator matrix as shown in equation 14

$$\mathbf{Q} = \begin{bmatrix} -\lambda_{12} & \lambda_{12} & 0 & \cdots & 0 \\ \lambda_{21} & -(\lambda_{21}+\lambda_{23}) & \lambda_{23} & 0 & \vdots \\ 0 & \lambda_{32} & -(\lambda_{32}+\lambda_{34}) & \lambda_{34} & \vdots \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_{M(M-1)} & -\lambda_{M(M-1)} \end{bmatrix} \tag{11}$$

$$\boldsymbol{\pi}\mathbf{Q} = \mathbf{0} \tag{12}$$
$$\sum_i \boldsymbol{\pi}_i = 1 \tag{13}$$
$$p_{ij}(t) = \left[e^{t\mathbf{Q}}\right]_{ij} \tag{14}$$

Parameter	Value	Unit
Simulation iterations	25000	[.]
Default mean delay	0.2	[s]
Mean delay range	[0.05,5]	[s]
rate of flexibility change, λ	1	$[s^{-1}]$
number of flexibility states	20	[.]
Default rate of periodic update, τ	4	$[s^{-1}]$
Rate of periodic update range, τ	[1,20]	$[s^{-1}]$
Rate of voltage events	0.33333	$[s^{-1}]$

Table I
PARAMETERS USED TO OBTAIN THE RESULTS SHOWN IN THIS SECTION.

Using this model, the probability of information mismatch for a given time horizon can be calculated as shown in equation 15.

$$Pr(mm|t) = \sum_{i=1}^{M} \left(\boldsymbol{\pi}_i \sum_{j=1}^{i-1} p_{ij}(t) \right) \tag{15}$$

The complete mmPr model can now be written out for each access scheme.

$$Pr(mm_{\text{Rea}}) = \int_0^\infty \sum_{i=1}^{M} \left(\boldsymbol{\pi}_i \sum_{j=1}^{i-1} p_{ij}(t) \right) (f_u * f_d)(t) dt \tag{16}$$

$$Pr(mm_{\text{Per}}) = \int_0^\infty \sum_{i=1}^{M} \left(\boldsymbol{\pi}_i \sum_{j=1}^{i-1} p_{ij}(t) \right) (f_d * f_w)(t) dt \tag{17}$$

V. ANALYSIS OF PARAMETER IMPACT ON MMPR

To obtain the results shown in this section, we assume exponentially distributed network delays. For each result shown, a single parameter is varied within the given range, and all other parameters kept constant at a default value. These parameter values are shown in table I. The Markov chain used in this evaluation is assumed to have equal rates of state change everywhere (i.e. $\lambda_{ij} = \lambda$ where $j = i + 1$ for $i < M$ and $j = i - 1$ for $i > 1$).

Figures 7 and 8 show the time distributions of mismatching time and response times respectively. Here it is seen that while the reactive scheme provides the shortest mismatching times, it comes at the price of increased response times. The two proactive schemes provides identical response times, though the event based scheme provides higher mismatching times than the periodical. Given this high mismatching time, it is expected that the event based scheme provides the highest mmPr, and the reactive scheme the smallest.

Figure 9 shows the change in mmPr when the mean delay of the network is increased. Here it is seen, in contrast to the time densities, that the periodical scheme provides the highest mmPr for low network delays, but equal to the event driven scheme for higher delays. The event driven scheme, provides equal mmPr than the reactive scheme for small delays, but performs better for high delays.

By varying the update rate of the periodical scheme, Figure 10 is produced. It is seen that at an update rate of 16 times the flexibility change rate, the periodic scheme starts to out perform the other schemes.

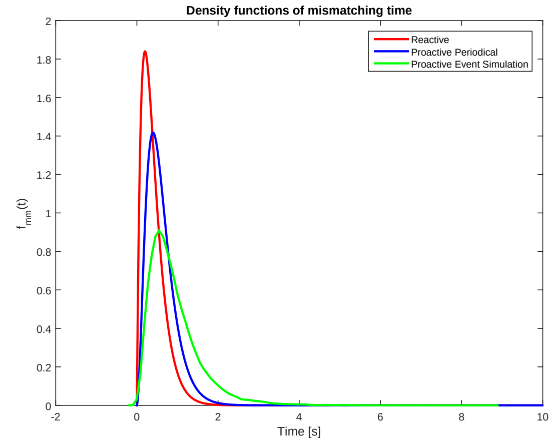

Figure 7. Density functions of mismatching time showing how the reactive scheme provides the smallest mismatching time of the three.

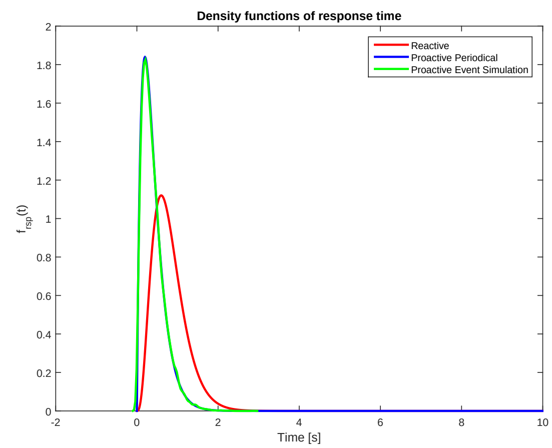

Figure 8. Density functions of response time showing the reactive scheme providing higher response times than the two other schemes.

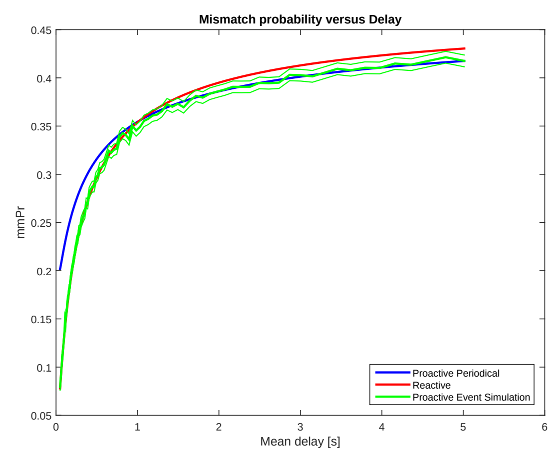

Figure 9. Mismatch probability versus Delay. Shown with 95% confidence intervals in dashed lines for the simulated results.

The trade off between mmPr and response time is shown in Figure 11, where it is seen that the periodical scheme can provide both low mmPr and low response time; however, as

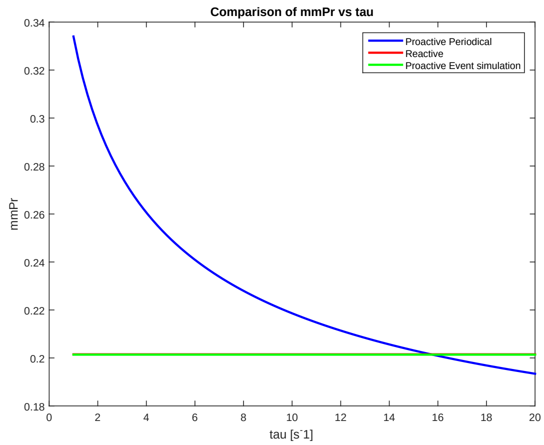

Figure 10. Mismatch probability versus periodical update rate.

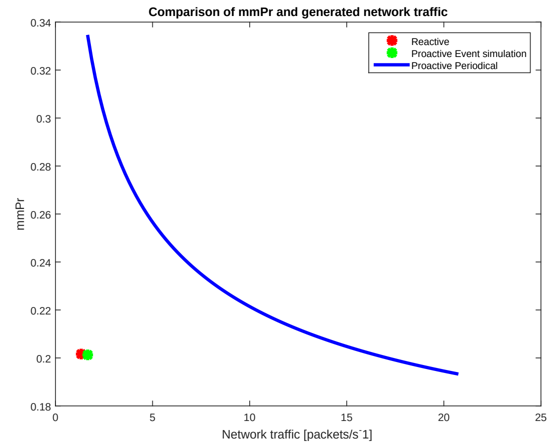

Figure 12. Mismatch probability versus generated network traffic in packets.

seen on Figure 12 it comes at the cost of large amounts of network traffic generation. Here it is also seen how low mmPr and low network traffic generation can be achieved using the reactive scheme. However, the impact of the increased response time on control performance is yet to be seen.

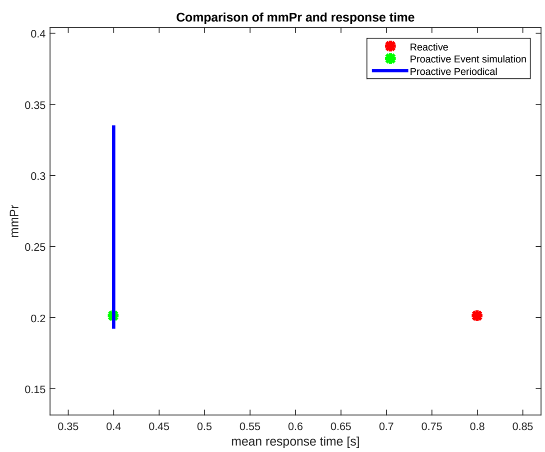

Figure 11. Mismatch probability versus response time.

VI. Conclusion

In this paper we consider communication network optimization of a low voltage grid controller in a smart grid setting. We define models for information dynamics and communication network delays, and present models for mmPr evaluation of communication networks. These models are developed so they can be generalized to any controller using similar communication patterns during operation. We consider three different information access schemes as optimization parameter for the communication network, reactive, proactive with periodic updates and proactive with event driven updates. The three access schemes where evaluated partly analytically and partly through simulations. Through this evaluation we show how information access optimality is a trade-off between response time, mmPr and used network resources. We show how network resources can be spent to achieve low response time and mmPr using the periodical scheme, how low mmPr and low network traffic generation can be achieved at the cost of response time through the reactive scheme, and finally how the event based scheme can provide a trade-off between all three.

In this paper we show how mmPr can be modelled and how different access schemes influence it. However, several topics remains for future studies like: Development of a feasible model for the event driven approach; determination of exact trade-offs using realistic information and delay models; determination of the influence of mmPr on actual control performance; and evaluation in a testbed implementation.

Acknowledgment

The research leading to these results has received funding from the European Communitys Seventh Framework Programme (FP7/20072013) under grant agreement No318023 for the SmartC2Net Project

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