METHOD AND DEVICE FOR SIGNALING AND CONTROLLING A POWER GRID COUPLING A PLURALITY OF ACTUATORS

A method for signaling and controlling in a power grid coupling a plurality of actuators for providing power signals is provided. In a first step at a first actuator of the actuators, a voltage problem is detected, a communication signal is generated based on the detected voltage problem and the generated communication signal is transmitted over the power grid. In a second step at a second actuator of the actuators, the transmitted communication signal is received, a control action is generated based on the received communication signal and the generated control action is transmitted over the power grid towards the first actuator. Advantageously, the control action is generated based on or as a function of the received communication signal. Thus, the first actuator may transparently use the help of the second actuator. Further, a computer program product and a device are provided.
Method and device for signaling and controlling a power grid coupling a plurality of actuators

The present invention relates to a method and to a device for signaling and controlling a power grid coupling a plurality of actuators for providing power signals.

In power grids, like energy distribution grids with high penetration of actuators like renewable energy sources, it is challenging to satisfy a quality requirement for the electricity, especially satisfying voltage limits and overloads of power components, like transformers or power lines.

The control of such grids is challenging because the control paradigm changed from few large power generators to many local small generators, e.g. voltaic generators, biogas generators or small wind turbines. These generators are weaker connected and due to their large number a coordinated control and the required communication are hard to realize.

For controlling power grids, model based control schemes may be used conventionally. Therein, the dependency of the voltage of the nodes in the power grid on the control variables, i.e. reactive and active power, is determined based on the electrical properties of the power grid. These electrical properties are either measured or obtained by modeling. Obtaining an accurate model, especially for distribution grids which are extensive in dimensions, is expensive and difficult to maintain disadvantageously.

In most conventional control schemes, dedicated communication channels are used. For example, mobile communication channels like 2G, 3G or 4G, Wimax, or wired communication, like Digital Subscriber Line (DSL), or Power Line Communication (PLC) may be used. Further, signaling in power systems is also achieved using so-called load management communication sy-
terns. In these systems, large power signals are used at frequencies in a range of 100 Hz to 2 kHz to inform loads about switching between different tariffs or to control the switching of loads. But these communications are only one-directional, from the power grid injection point to the loads, in particular broadcast. So, it cannot be used for signaling voltage problems between actuators in a power grid.

Accordingly, it is an object of the present invention to provide an improved signaling and controlling in a power grid.

According to a first aspect, a method for signaling and controlling in a power grid coupling a plurality of actuators for providing power signals is provided. In a first step at a first actuator of the actuators, a voltage problem is detected, a communication signal is generated based on the detected voltage problem and the generated communication signal is transmitted over the power grid. In a second step at a second actuator of the actuators, the transmitted communication signal is received, a control action is generated based on the received communication signal and the generated control action is transmitted over the power grid towards the first actuator.

Presently, the control action is generated based on or as a function of the received communication signal. Thus, the first actuator may transparently use the help of the second actuator or a device coupled to the second actuator forming a common node in the power grid.

As a result, a decentralized control is advantageously possible. Therefore, no extra central control unit is needed.

Furthermore, no topology information is needed. Further, by generating the control action in dependence on the communication signal, in particular on the amplitude of the communication signal, an optimal use of reactive and/or active in the power grid is possible.
Thus, the present control scheme may also be called self-organized control scheme. Furthermore, the present communication signal may be also called signaling signal, in particular because it is used for signaling a voltage problem to coupled actuators or nodes.

In the present method, the dependency of the control action on the voltage problem and therefore the communication signal may be detected online at the second actuator. Thus, the present control scheme may also be called model-free control scheme, where, in an example, only an analogue value for communicating the amount of the voltage problem has to be transmitted from the first actuator to the second actuator. Because of transmitting only one analogue value, no voltage band violations may occur. Further, no dedicated communication channel has to be used for transmitting the present communication signal, because it can be directly transmitted over the power grid.

The actuators coupled by the power grid may include inverters connected to generators and consumers where the active and/or the reactive power may be controlled, e.g. photovoltaic generators, storage systems, like stationary batteries or batteries from electro-mobility, or wind turbines, other generators and consumers that can control active power, e.g. fossil generators, combined heat and power generators, biogas generators, consumers with variable power and/or switching equipment, including transformers equipped with controllable tap changes.

The generated control action may include injecting active power, e.g. a current, into the power grid, injecting reactive power into the power grid and/or changing a transformer tap.
According to some implementations, the communication signal has a frequency which is close to the nominal frequency or fundamental frequency of the power grid. The advantage of using such a communication signal is that the level of the received signal is proportional with the grid impedance seen by the receiving actuator (second actuator). The grid impedance is the proportionality factor in the amount in which the receiving actuator may influence the voltage at the transmitting actuator using reactive and active power. In this way, the node or actuator having the voltage problem controls the help that it gets from other actuators automatically proportional with how much these actuators can influence the voltage at its connection in the power grid.

According to an embodiment, the control action is generated such that its amplitude is a function of the amplitude of the received communication signal.

In particular, the communication signal is transmitted over the power grid and has a frequency close to the fundamental frequency of the power grid. The advantage of using such a signal is that the level of the received communication signal is proportional with the grid impedance seen by the receiving actuator, grid impedance which is the proportionality factor in the amount in which the receiving actuator can influence the voltage at the transmitting actuator using reactive and active power. In this way, the actuator where the voltage problem appears controls the help that it gets from the other actuator or the other actuators automatically proportional with how much these actuators receiving the communication signal can influence the voltage at its connection.

According to a further embodiment, the control action is generated such that its amplitude is proportional to the amplitude of the received communication signal.
According to a further embodiment, the control action is generated at the actuator such that the following equation is fulfilled:

$$\frac{A_{TX}^C}{A_{RX}^P} = \frac{A_{RX}^C}{A_{TX}^P}$$

wherein $A_{TX}^C$ designates the amplitude of the generated communication signal at the first actuator,

wherein $A_{RX}^C$ designates the amplitude of the received communication signal at the second actuator,

wherein $A_{TX}^P$ designates the amplitude of the generated control action at the second actuator, and

wherein $A_{RX}^P$ designates the amplitude of the received control action at the first actuator.

By means of the above equation, the helping actuator may transparently help the actuator asking for help.

According to a further embodiment, at at least two second actuators of the plurality of actuators, the transmitted communication signal is received, a respective control action is generated based on the respective received communication signal and the respective generated control action is transmitted over the power grid towards the first actuator.

In particular, a plurality of actuators may help the actuator asking for help by the communication signal using different control actions. The control actions of the plurality of second actuators are different because they receive a different level of the communication signal in the power grid, respectively.

According to a further embodiment, the communication signal is a current injected into the power grid by the first actuator.

The communication signal is modulated onto the power signals.
According to a further embodiment, the communication signal is generated such that the current has a frequency that is proportionally related to the fundamental frequency of the power signals transmitted by the actuators over the power grid.

According to a further embodiment, the communication signal is generated such that the current is a harmonic of the fundamental frequency of the power signals transmitted by the actuators over the power grid.

It is an advantage to use harmonics of the power signal for the communication signal because the fundamental frequency or fundamental component (50 Hz) is present at all the nodes (actuators) with identical frequency and may be used to provide synchronization for the communication.

According to a further embodiment, the communication signal is generated such that the current is an even harmonic, in particular a second harmonic, of the fundamental frequency of the power signals transmitted by the actuators over the power grid.

Even harmonics are almost interference free and only affect a background noise of about 0.06 %. Further, the communication may be synchronized by the fundamental component (50 Hz) which has the same frequency everywhere in the grid. Further, the relevant norms allow up to 2 % amplitude of the signal which is sufficient for detection at the actuators. It is shown that the level of the even harmonics is very low while the one of the odd ones may be significant (see reference [2]).

According to a further embodiment, the communication signal is generated such that the current is an inter-harmonic of the fundamental frequency of the power signals transmitted by the actuators over the power grid.
Also the use of inter-harmonics, e.g. 3/4 of the fundamental frequency, or 4/5 of the fundamental frequency, is possible. The modulation and especially demodulation may be more complex using inter-harmonics. The advantage of the harmonics is that in one period of the fundamental frequency an integer number of the periods of the harmonics may be sent and detected. The synchronization of the transmission and of the detection may be realized by the beginning of the period of the fundamental frequency. In case of inter-harmonics either multiple periods of the fundamental frequency has to be used for the transmission as an alternative, complete periods of the inter harmonics may be transmitted. In the first case, a synchronization of the bursts has to be realized. In the second case, the detection may be distorted.

According to a further embodiment, the communication signal is modulated by On/Off-keying.

The use of On/Off-keying, On/Off-modulation or an alternative time multiple access scheme facilitates the sending of stronger signals and also the detection of possible interference on the same harmonics. Further, still the norms on the mean RMS (root mean square) value are satisfied by detecting and cancelling the interferences, the robustness of the whole system may be increased. Moreover, an estimation of the number of the transmitters in the power grid may be facilitated, in particular by evaluating the number of the occupied slots in one transmission period.

According to a further embodiment, the modulated communication signal is synchronized by the fundamental frequency of the power signals.

The fundamental frequency or fundamental component of the power signals is used for synchronizing the communication, in particular the communication signals. The fundamental component has the same frequency at all the nodes of the power grid and phase differences are very small, in particular in
distribution grids. Consequently, in the case of multiple transmitters, the signals are going to add up in phase and also the timing of the On/Off-modulation may be realized. Thus, in phase transmission from different transmitters is facilitated. Without this synchronization it might be that the signals from different transmitters are canceling each other out. Detecting the phase of the transmitted signals is possible because the fundamental component may act as phase reference. Furthermore, time division of the transmission period is facilitated, which is used in the On/Off-modulation.

According to a further embodiment, as long as a voltage problem is detected at the first actuator, a communication signal is generated based on the detected voltage problem and transmitted over the power grid each transmission period, wherein the transmission period includes N periods of the fundamental frequency of the power signals, with N ≥ 2.

As long as the voltage problem remains at the first actuator, a communication signal is transmitted over the power grid. The communication signal transmitted over the power grid may change in its level over time. The change of the level is dependent on the level of the detected voltage problem.

According to a further embodiment, the following steps are executed at the first actuator:
- detecting the fundamental frequency of the power signals,
- defining the transmission period with N transmission slots,
- selecting one transmission slot within the N transmission slots for transmitting the communication signal,
- calculating an amplitude of the current of the communication signal based on the detected voltage problem, and
- injecting the current with the calculated amplitude and the frequency of the second harmonic of the fundamental frequency of the power signals in the selected transmission slot into the power grid.
Any embodiment of the first aspect may be combined with any embodiment of the first aspect to obtain another embodiment of the first aspect.

According to a second aspect, the invention relates to a computer program product comprising a program code for signaling and controlling in a power grid coupling a plurality of actuators providing power signals when run on at least one computer.

A computer program product, like a computer program means, may be embodied as a memory card, USB stick, CD-ROM, DVD or as a file which may be downloaded from a server in a network. For example, this may be provided by transferring the respective file with the computer program product from a wireless communication network.

According to a third aspect, a device for signaling and controlling a power grid coupling a plurality of actuators providing power signals is provided. The device includes a first entity and a second entity. The first entity is coupleable with a first actuator of the actuators and configured to generate a communication signal based on a detected voltage problem and to transmit the generated communication signal over the power grid.

The second entity is coupleable with a second actuator of the actuators and configured to receive the transmitted communication signal, to generate a control action based on the received communication signal and to transmit the generated control action over the power grid towards the first actuator.

The device may be a plug-and-play-device which is coupleable with any actuator in the power grid. Thus, the configuration is very simple and no expert knowledge is needed.
The respective means, e.g. the first entity and the second entity, may be implemented in hardware and/or in software. If said means are implemented in hardware, it may be embodied as a device, e.g. as a computer or as a processor or as a part of a system, e.g. a computer system. If said means are implemented in software it may be embodied as a computer program product, as a function, as a routine, as a program code or as an executable object.

According to a fourth aspect, a power grid is provided which couples a plurality of actuators for providing power signals. Each of the plurality of actuators comprises a device of above-mentioned third aspect.

Further objects, features and advantages of the present invention will become apparent from the subsequent description and depending claims, taking in conjunction with the accompanying drawings, in which:

Fig. 1 shows an embodiment of a sequence of method steps for signaling and controlling in a power grid coupling a plurality of actuators;

Fig. 2 shows a first example of a representation of a power grid;

Fig. 3 shows a first example of a representation of a power grid;

Fig. 4 shows a diagram illustrating the fundamental frequency of the power grids and some harmonics;

Fig. 5 shows a time curve of the amplitude of the second harmonic of Fig. 4;

Fig. 6 shows a time curve of the amplitude of the third harmonic of Fig. 4;
Fig. 7 shows a time curve of the amplitude of the fourth harmonic of Fig. 4;

Fig. 8 shows a time curve of the amplitude of the fifth harmonic of Fig. 4;

Fig. 9 shows a representation of the transmission operation of communication signals;

Fig. 10 shows a representation of the signal selected for detection; and

Fig. 11 shows an embodiment of a device for signaling and controlling in a power grid coupling a plurality of actuators.

In the Figures, like reference numerals designate like or functionally equivalent elements, unless otherwise indicated.

In Fig. 1, a first embodiment of a sequence of method steps for signaling and controlling in a power grid $G$ (see Fig. 2 or 3) coupling a plurality of actuators $A, B, C$ for providing power signals is depicted.

In step 101, at the actuator $B$ of the actuators $A, B, C$, a voltage problem is detected. In case that a voltage problem is detected, a communication signal $I_B$ based on the detected voltage problem is generated at the actuator $B$. Then, the generated communication signal $I_B$ is transmitted over the power grid $G$ by the actuator $B$. In this regard, Figs. 2 and 3 show simple representations of the power grid $G$. In Figs. 2, 3, $Tx$ indicates the transmitting node, here $B$, where $Rx$ indicates the receiving node, in Fig. 2 node or actuator $A$, and in Fig. 3 nodes or actuators $A, C$.

In the examples of Figs. 2 and 3, the actuator $B$ may be also called transmitting ($Tx$) actuator or first actuator, and the
actuators A and C may be also called receiving (Rx) or second actuators.

For example, the communication signal $I_B$ is a current injected into the power grid $G$ by the actuator $B$. In particular, the communication signal $I_B$ is generated such that the current has a frequency that is proportionally related to the fundamental frequency of the power signals transmitted by the actuators $A$, $B$, $C$ over the power grid $G$. For example, the fundamental frequency is 50 Hz.

In particular, the communication signal $I_B$ is modulated by On/Off-keying. Further, the modulated communication signal $I_B$ is synchronized by the fundamental frequency (50 Hz) of the power signals. This is also explained later in very detail.

In step 102, at a second actuator $A$, $C$ of the actuators $A$, $B$, $C$, the transmitted communication signal $I_B$ is received. In response of receiving such a transmitted communication signal $I_B$, a control action $I_A$, $I_C$ is generated based on the received communication signal $I_B$. In other words, there is a direct link between the received communication signal $I_B$ and the generated control action $I_A$, $I_C$. Then, the generated control action $I_A$, $I_C$ is transmitted by the second actuator $A$, $C$ over the power grid $G$ towards the first actuator $B$.

In particular, the control action $I_A$, $I_C$ is generated such that its amplitude is a function of the amplitude of the received communication signal $I_B$. In particular, the control action $I_A$, $I_C$ is generated such that its amplitude is proportional to the amplitude of the received communication signal $I_B$.

In particular, the control action $I_A$, $I_B$ is generated at a second actuator $A$, $C$ such that the following equation is fulfilled:
wherein \( A_{TRX} \) designates the amplitude of the generated communication signal \( I_B \) at the first actuator \( B \),

wherein \( A_{RX} \) designates the amplitude of the received communication signal \( I_B \) at the second actuator \( A, C \),

wherein \( A_{TX} \) designates the amplitude of the generated control action \( I_A, I_C \) at the second actuator \( A, C \), and

wherein \( A_{RX} \) designates the amplitude of the received control action \( I_A, I_C \) at the first actuator \( B \).

For the case that at least two second actuators \( A, C \) of the plurality of actuators \( A, B, C \) are receiving the transmitted communication signal \( I_B \), as shown in Fig. 3, a respective control action \( I_A, I_C \) is generated based on the respective received communication signal \( I_B \), and the respective generated control action \( I_A, I_C \) is transmitted over the power grid \( G \) towards the first actuator \( B \). Because of the different impedances \( Z_A, Z_M, Z_C \) at the different nodes \( A, C \), also the received communication signals \( I_B \) are different at the different nodes \( A, C \).

As long as a voltage problem is detected at the first actuator \( B \), a communication signal \( I_B \) is generated based on the respective detected voltage problem and transmitted over the power grid \( G \) within each transmission period. The transmission period includes \( N \) periods of the fundamental frequency (50 Hz) of the power signals.

In more detail, for the example of Fig. 2, it is assumed that there is a voltage problem in the actuator (node) \( B \). The node \( B \) generates a communication signal \( I_B \) for requesting the help of the actuator in node \( A \) by injecting a current \( I_B \). Then, the voltage variation measured in node \( A \) due to this current will be: \( \Delta \upsilon_A = Z_A \cdot I_B \).
If the receiver injects a current proportional with $\Delta \nu_A$ ($I_A = \alpha \cdot \Delta \nu_B$) in node $A$, then the voltage difference observed at node $B$ will be $\Delta \nu_B = Z_A \cdot \alpha \cdot Z_A \cdot I_B$.

The variation of the voltage at node $B$ which has a voltage problem, produced by actuator $A$, controlled by the injected current $I_B$ will be $\Delta \nu_B$ proportional with $I_B$. Consequently, the actuator in node $B$ is able to use transparently the help of the actuator in node $A$, whose response is proportional with the control variable $I_B$.

Further on, considering a more complex power grid $G$ with several branches as exemplarily depicted in Fig. 3, then it can be observed that the measured signal at node $A$ is $\Delta \nu_A = (Z_A + Z_T) \cdot I_B$ and the measured signal at node $C$ is $\Delta \nu_C = (Z_T \cdot I_B)$, smaller than the one in node $A$. But also the help that node $A$ can provide is equal to $(Z_A + Z_T) \cdot I_A$, larger than that node $C$ can provide which is $Z_T \cdot I_C$, for the same injected current $I_B$. Consequently, the node which can help more (node $A$) will be the first and the strongest that will help. This results in an effective use of the available control resources, in particular reactive and active power.

As mentioned above, the communication signal is in a frequency range, so that the power grid impedance at the fundamental frequency of the power grid (50 Hz) can be deduced. At frequencies different than the fundamental frequency, grid norms are imposing limitations for the perturbation and the communication can be made more reliable.

Nevertheless, it has to be taken care that also with the communication signal the norms are not violated. Thus, the use of harmonics of the power signals (50 Hz) is advantageous, because the fundamental frequency (50 Hz) is present at all the nodes with identical frequency and can be used to provide synchronization for the communication. In particular, the communication signal $I_B$ is generated such that the current is
a harmonic of the fundamental frequency of the power signals transmitted by the actuators A, B, C over the power grid G.

For example, in reference [1], it is shown how the harmonics are produced by different equipments, with focus on power electronic inverters. It is shown that only odd harmonics are usually excited (third, fifth, and so on), while in principle the even ones (second, fourth, and so on) are not produced. Furthermore, in reference [2], it is shown that the level of the even harmonics is very low, while the one of the odd harmonics is significant. This is depicted in Fig. 4.

Furthermore, measurements in a distribution grid of AïW energy provided during a certain project, namely the IRENE project, were performed. These measurements are given in Figs. 5 to 8 and confirm the observation of Fig. 4, namely that it is very advantageous to use the even order harmonics for the communication signal to keep the properties of the power grid as similar as possible and to avoid interference with the communication load management systems. The second harmonics are preferably used.

The frequency of the second harmonics lies below the frequencies used in the load management system. If from any reasons, the second harmonic is perturbed, the 4th harmonics can also be used. The load management systems do not pose a real interference, because their signals are transmitted seldom and have a short duration.

In the grid impedance, the resistive part is the same at the fundamental frequency and at the harmonics. The reactive part is directly proportional with the frequency, so the reactive part is multiplied with the harmonic number compared with the reactance at the fundamental frequency.

As mentioned above, the use of inter-harmonics, e.g. 3/4 of the fundamental, 4/5 of the fundamental is also possible, but the modulation and especially the demodulation are more com-
plex. The advantage of the harmonics is that in one period of the fundamental an integer number of the periods of the harmonics can be sent and detected. The synchronization of the transmission and of the detection is realized by the beginning of the period of the fundamental frequency. In the case of inter-harmonics this is not satisfied, so either multiple periods of the fundamental frequencies have to be used for the transmission, or not complete periods of the inter-harmonics are sent. In the first case, a synchronization of the bursts has to be realized. In the second case, the detection is distorted.

Moreover, the On/Off-modulation scheme may be used from transferring the communication signals.

In the norm EN 61000-3-2 (VDE 0838-2) for example, it is described which requirements are imposed on the electrical devices so that they are allowed to be connected to the electrical grid. In this norm, it is described which are the maximum currents which are allowed to be injected at different harmonics of the power signal.

For the second harmonics, it is requested that the RMS mean value of the current over 1.5 seconds can be maximally 1.08A and this can be excelled with maximum 150%.

A typical cable used in low voltage distribution grids (NAVY 4x150) has the following electrical properties:

\[ R = 0.206 \, \text{Ohm/km} \]
\[ X = 0.080 \, \text{Ohm/km} \]

Injecting a power of 25 kW at the end of a cable of 1 km, it results a voltage increase (roughly computed):

\[ AU = \frac{(P/3)}{U_N} \times R = 7.2 \, \text{V} \approx 3\% \]
This value is the voltage increase with normally the grid operators are allowing to happen in the low voltage part of the distribution grid. At this level, the inverter should be able to transmit a detectable signal for coordination of the voltage control.

The amplitude of the second order harmonics signal that can be achieved over such a line using a current of 1A is:

\[ \text{AU}_{100} = i_{100} \times (R + jX) = 0.2 + j0.16 \text{ V} \]

This signal is much too small, being very easy to be perturbed by noise.

The solution to avoid this limitation is to transmit the second harmonic signal only for a short period of time and then not to transmit it for a while. Then, the RMS mean will be smaller than the peak which is transmitted.

For synchronization, the fundamental frequency is used. A transmission period is defined as a group of N periods of the fundamental component. This transmission period is then divided in N slots, each slot of the length of one fundamental period. For one slot, the second harmonic is transmitted (2 periods of the harmonic), while the other N-1 periods no signal is transmitted. This way, all the receiving nodes or receivers know that they have to receive over N periods of the fundamental of the power signal (50 Hz), and if there is a signal, this will be in one of the slots.

For example, a number of \( N = 50 \) slots of approximately 20 ms is considered, then the transmission period will be 1 second. If the current is injected for 1 slot, i.e. 1/50 periods of the time, then maximum amplitude of 7A for the second harmonics can be allowed, and the RMS value over the period will be \( \sqrt{7^2 / 50} \equiv 1 \text{A} \).

The measurable signaling voltage over the 1 km line will be
\[ A \cdot \text{ioo } \text{ON/OFF} = \text{ioo } \text{ON/OFF} \times (R + 2X) = 1.4 + 1.12 \text{ V} \]

which can be detected very well.

The power of the signal during the transmission may be
\[ S = \text{abs}(U \times I) \approx 12.5 \text{ VA}, \]
while the average power may be
\[ 0.25 \text{ VA}, \]
which can be easily implemented with electronics components.

For the communication, an On/Off-modulated communication signal is transmitted, the signal consisting of two periods of the second harmonics of the fundamental frequency.

Definitions:
- Transmission period (shortly termed period): Period of the transmission consisting of \( N \) periods of the fundamental frequency. The processing is performed over one period, and the signals are repeated each period.

- Transmission slot (short termed slot): has the duration of one period of the fundamental frequency. The slot starts when the fundamental component represented as a sinusoid has zero phase, i.e. the voltage line to neutral is 0 and it is increasing, see representation in Figure 6.

- Transmitter: element in the communication scheme which has a voltage problem and is transmitting a signal to control potential actuators that can receive its signal and can help compensate the voltage. In particular, the transmitters are termed masters. There can be several transmitters simultaneously.

- Receiver: all the elements in the communication scheme which can help in the voltage problem. These are also the transmitters. In particular, the receivers are termed slaves.
Parameters:
- \( N \) - number of slots in one period, e.g. \( N = 50 \);
- \( I_{\text{ioomax}} \) - maximum current used for the communication signal, corresponding to transmitting the maximum value from the controller. The values needed to be transmitted are analogue values between 0 and 1 and these are mapped to second harmonics current between 0 and \( I_{\text{ioomax}} \). Example: \( I_{\text{ioomax}} = VA \)

Operation:
1. Each transmitter detects the fundamental component of the power signal, frequency and phase.

This detection is used by each transmitter to define the transmission period and each slot.

Notice that the periods may not be synchronous between the different transmitters - the periods might start at different moments, different multiples of the fundamental component period. Nevertheless the slots are almost synchronous, being synchronized by the fundamental component.

The difference between the slots of different transmitters and different receivers appears due to phase shift of the fundamental frequency between different nodes. Nevertheless, this phase shift is very limited in the distribution grids, even for extreme cases.

2. Each transmitter is defining the period of \( N \) slots. It selects randomly one slot in which it transmits.

3. Before each transmission, the transmitter reads from the controller at the node the value that needs to be transmitted, value which is normalized between 0 and 1. This value is mapped to a current between 0 and \( I_{\text{ioomax}} \).
4. The transmitter is injecting the second harmonics current in the selected slot. The current is also a sinusoid which starts with phase 0 at the beginning of the slot.

5 The above operation is illustrated in Fig. 9 for two masters, with N = 5. With vertical longer lines 901 is marked the beginning of the periods of the transmission, each N periods of the fundamental component and with shorter lines 902 the beginnings of the slots (one is overlapping with the beginning of the period). Notice that the periods are not synchronized between the transmitters (masters). The slots start when the fundamental is crossing the zero line and the voltage is increasing. According to the upper subimage of Fig. 9, the first master is injecting the second harmonics current at the slot 3, while the second in the slot 1. The frequency of the fundamental component is 50.05 Hz (different than the nominal frequency of 50 Hz) and there is a phase difference of 3 degrees between the fundamental components. These very small differences cannot be visualized in Fig. 9.

The signal detection is performed by each participant in the communication grid, no matter if it is also at the same time a transmitter. In the signal detection, the total amplitude of the communication signal has to be estimated, i.e. in the On/Off-modulation, the sum signal transmitted in all the slots is estimated. Additionally, due to the design so that the number of slots is substantially larger than the number of transmitters, interference can be detected and canceled from the signal, as it will be described later in this section.

Parameters (fixed, defined for the system):
- N - number of slots in one period, e.g. N = 50;
- M - upper bound on the number of possible transmitters, e.g. M = 25. This parameter is used in the detection of any continuous interference, using the fact that if there are no more than M transmitters, then in N-M slots
only the interference should be present. Even if there are more than M transmitters, they select their slots randomly, so it is very likely that many will be overlapping and still there will be at least N-M slots there no communication transmitter is sending a signal and the interferer is received alone.

- \( \Delta \theta_{\text{int}} \) - Thresholds used in deciding if the signal is the same in different slots. For example, the detection errors are in the range of:
  \[ \Delta \phi_{\text{int}} = 0.1 \text{ Volt} \text{ and } A\phi_{\text{int}} = 3 \text{ degrees} \].

- \( \Delta \theta_{\text{sen}} \) - sensitivity on the detection of the second harmonics, threshold used for deciding if in a slot there is useful signal that should be added to the total communication signal. Not all the slots are added up to avoid summing up only noise. \( A_{\text{sen}} \) has similar meaning with \( A\phi_{\text{int}} \) and can be set to the same value \( A_{\text{ens}} = 0.1 \text{ V} \).

**Operation:**
1. Each receiver detects the fundamental component of the power signal, amplitude, frequency and phase:

This step is the same as in the case of the transmission, both operations can use the same implementation and process.

The tracking of the fundamental component should be performed continuously to avoid errors due to the variation of the frequency and more importantly propagation and increase of the phase error due to small errors in the frequency estimation.

At least two periods plus a few samples to compensate for frequency differences between the fundamental and the nominal frequency are needed. In the processing roughly three periods of the fundamental are going to be selected, starting from approximately the middle of the period, see Fig. 10. In the upper subimage of Fig. 9, the received signal \( r \) is depicted,
wherein the lower subimage of Fig. 9 shows the second harmonics.

For selecting the period of signal for analysis, the precision does not need to be high. The algorithm itself described in the above-mentioned report is then processing the data so that the orthogonality of the signals is best achieved.

2. Detect communication signal in the first slot (complete fundamental period) of the selected signal:

In Fig. 10, it is shown the case that the 2nd harmonics is present in the first slot (from t=0.01 to t=0.02s). The exact beginning and end of the slot are computed based on the frequency and phase of the fundamental, detected at step 1.

The detection of the second harmonics has two steps:
- the fundamental component is subtracted from the received signal, to eliminate the strongest interference from the detection.
- then the second harmonic is detected with the method presented in the above-mentioned report or using simple FFT or the Goertzel method (see reference [3]).

For the detected slot, the amplitude and the phase of the second order harmonics is stored.

Data from next period of the fundamental is collected and points 1 and 2 are repeated until data is detected for N slots, i.e. one period of the On/Off-modulation.

3. On/Off-processing with interference suppression:

First, it is checked if there is any interferer present. An interferer can be recognized in that it is detected in sever-
al slots with same amplitude and phase, i.e. it is transmitting continuously and not in only one slot.

If there are $N$ slots and $M$ is the upper bound on the number of transmitters, then the interferer should be received alone, not superimposed with the communication transmissions, in at least $N - M$ slots. Consequently, it should be detected with the same (up to the detection error, $\Delta A_{\text{int}rf}, \Delta \varphi_{\text{int}rf}$) amplitude and phase. Notice that if interference and useful signal are superimposed in one slot, than this slot is going to have a different amplitude and phase than a slot where only the interferer is present. Also, if there are several interferers, they will be detected as an interferer with amplitude and phase equal with the trigonometric sum of the interferers. This does not have any impact on the detection of the communication scheme.

If an interferer has been identified, the amplitude and the phase of the interferer is computed as the mean of the detected amplitudes and the mean of the phases in the slots marked as interferer only slots.

Next, the slots with useful signal are identifier, as the slots where the detected amplitude is above a predefined noise level ($A_{\text{sens}}$) and it was not previously identified as slot with interferer only.

If an interferer was detected, then the signal of the interferer is subtracted from all the slots with useful signal.

Given two sinus signals (communication modulation and interference), the sum of the signals is also a sinus signal. The communication signal can be obtained back by making the difference from the received sinus signal and the detected interferer:

$$A \sin(\omega t + a) + B \sin(\omega t + \beta) =$$
The sum communication detected signal is computed next as the sum of the estimated useful signals. The sum is done trigonometrically with the equation above.

4. Output normalization:

For the control input the received signal is normalized.

To avoid producing a control signal due to noise only, the signals that are below the noise level are set to zero, so output signal is zero.

For the control of the voltage with reactive power, only the part of the signal depending on the grid reactance is selected. This is equal with the imaginary part of the complex representation of the detected amplitude and phase.

Finally the value is normalized to the detected signal in the case the device would be transmitting with full current \( I_{\text{ioomax}} \) alone, value which is proportional also with the grid reactance. To determine this value, the device is going to transmit the communication signal for a short period when for sure there are no voltage problems.

The following criteria may be followed to ensure that no other communication signal is present:

1. The detection is performed and no communication signal is detected.

2. Locally measured voltage value is below a given threshold, e.g. \( U < 102\% \) of the nominal value.
The estimation of the grid should be performed regularly, every few hours or days.

To further avoid that, because of sudden changes of the voltage in the grid (e.g. in the case of tap changes), several communication devices are trying to estimate the grid simultaneously, a random delay should be implemented so that the signal transmission is performed after a random time (e.g. 1 to 1000 periods of the fundamental).

If the signal estimated in the above procedure is below the noise level $\mu_{\text{noise}}$, then the device is strongly connected to the grid and it will not be able to influence the voltage with reactive power. It should not participate in the control scheme, so the output is always set to zeros.

Otherwise, the signal sent to the controller by the communication unit will be the reactive part of the detected sum signal from point 4, normalized to the detected reactive part when the device is transmitting with full current by itself.

Fig. 11 shows an embodiment of a device 10 for signaling and controlling a power grid $G$ coupling a plurality of actuators A, B, C providing power signals. The device 10 is coupleable to an actuator or node in the power grid $G$. The device 10 comprises a first entity 11 and a second entity 12. It may be noted that the first entity 11 communicates with second entities of other nodes. In an analogous way, the second entity 12 of the device 10 of Fig. 11 communicates with first entities of other nodes.

The first entity 11 is configured to generate a communication signal $CS$ in a case that the coupled node has a voltage problem. Then, the first entity 11 transmits the generated communication signal $CS$ over the power grid $G$.

The second entity 12 is configured to receive a transmitted communication signal $CS$ from another node, to generate the
control action CA based on the received communication signal CS and to transmit the generated control action CA over the power grid G towards the sender of the communication signal CS.

In detail, the first entity 11 includes a receiver 13 for receiving signals from the grid G, in particular voltage U and current I. Because the communication signal CS is a current modulated on the power signals of the power grid G, it is particularly received as a current I at the receiver 13. Further, the first entity 11 includes a controller 14 for controlling a signal generator 15 which generates the communication signal CS in dependence on the respective detected voltage problem. Furthermore, the controller 14 is configured to provide a command CO for generating the control action to the second entity 12.

Although the present invention has been described in accordance with preferred embodiments, it is obvious for a person skilled in the art that modifications are possible in all embodiments.
References


Claims

1. A method for signaling and controlling a power grid (G) coupling a plurality of actuators (A, B, C) for providing power signals, the method comprising:
   - at a first actuator (B) of the actuators (A, B, C), detecting (101) a voltage problem, generating a communication signal (I_B) based on the detected voltage problem and transmitting the generated communication signal (I_B) over the power grid (G), and
   - at a second actuator (A, C) of the actuators (A, B, C), receiving the transmitted communication signal (I_B), generating a control action (I_A, I_c) based on the received communication signal (I_B) and transmitting the generated control action (I_A, I_c) over the power grid (G) towards the first actuator (B).

2. The method of claim 1, wherein the control action (I_A, I_c) is generated such that its amplitude is a function of the amplitude of the received communication signal (I_B), in particular such that its amplitude is proportional to the amplitude of the received communication signal (I_B).

3. The method of claim 1 or 2, wherein the control action (I_A, I_c) is generated at the second actuator (A, C) such that the following equation is fulfilled:

\[
\frac{A_{TX}}{A_{RX}} = \frac{A_{TX}}{A_{RX}}
\]

wherein A_{TX}^C designates the amplitude of the generated communication signal at the first actuator,
wherein A_{RX}^C designates the amplitude of the received communication signal at the second actuator,
wherein A_{TX}^p designates the amplitude of the generated control action at the second actuator, and
wherein $A_{Rx}^p$ designates the amplitude of the received control action at the first actuator.

4. The method of one of claims 1 to 3, wherein, at at least two second actuators $(A, C)$ of the plurality of actuators $(A, B, C)$, the transmitted communication signal $(I_B)$ is received, a respective control action $(I_A, I_C)$ is generated based on the respective received communication signal $(I_B)$ and the respective generated control action $(I_A, I_C)$ is transmitted over the power grid $(G)$ towards the first actuator $(B)$.

5. The method of one of claims 1 to 4, wherein the communication signal $(I_B)$ is a current injected into the power grid $(20)$ by the first actuator $(B)$.

6. The method of claim 5, wherein the communication signal $(I_B)$ is generated such that the current has a frequency that is proportionally related to the fundamental frequency of the power signals transmitted by the actuators $(A, B, C)$ over the power grid $(G)$.

7. The method of claim 5 or 6, wherein the communication signal $(I_B)$ is generated such that the current is a harmonic of the fundamental frequency of the power signals transmitted by the actuators $(A, B, C)$ over the power grid $(G)$.

8. The method of claim 5 or 6, wherein the communication signal $(I_B)$ is generated such that the current is an even harmonic, in particular a second harmonic, of the fundamental frequency of the power signals transmitted by the actuators $(A, B, C)$ over the power grid $(G)$.

9. The method of claim 5 or 6, wherein the communication signal $(I_B)$ is generated such that the current is an inter-harmonic of the fundamental frequency.
10. The method of one of claims 1 to 9, wherein the communication signal ($I_B$) is modulated by On/Off-keying.

11. The method of claim 10, comprising:  synchronizing the modulated communication signal ($I_B$) by the fundamental frequency of the power signals.

12. The method of claim 10 or 11, wherein, as long as a voltage problem is detected at the first actuator (B), a communication signal ($I_B$) is generated based on the detected voltage problem and transmitted over the power grid (G) each transmission period, wherein the transmission period includes N periods of the fundamental frequency of the power signals.

13. The method of claim 12, comprising:
   - detecting the fundamental frequency of the power signals,
   - defining the transmission period with N transmission slots,
   - selecting one transmission slot within the N transmission slots for transmitting the communication signal,
   - calculating an amplitude of the current of the communication signal based on the detected voltage problem, and
   - injecting the current with the calculated amplitude and the frequency of the second harmonic of the fundamental frequency of the power signals in the selected transmission slot into the power grid.

14. Computer program product comprising a program code for executing the method of one of claims 1 to 13 when run on at least one computer.
15. A device (10) for signaling and controlling a power grid (G) coupling a plurality of actuators (A, B, C) providing power signals, the device (10) comprising:

- a first entity (11) coupleable with a first actuator of the actuators and configured to generate a communication signal (CS) based on a detected voltage problem and to transmit the generated communication signal (CS) over the power grid (G), and
- a second entity (12) coupleable with a second actuator of the actuators and configured to receive the transmitted communication signal (CS), to generate a control action (CA) based on the received communication signal (CS) and to transmit the generated control action (CA) over the power grid (G) towards the first actuator.
**INTERNATIONAL SEARCH REPORT**

**PCT/EP2013/065744**

**A. CLASSIFICATION OF SUBJECT MATTER**

INV. H02J3/12  H02J13/00  H02J3/38

ADD.

According to International Patent Classification (IPC), the following national classification and IPC:

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H02J  H02X  G05F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched.

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>US 2013/134779 A1 (WATANABE KENICHI [JP] ET AL) 30 May 2013 (2013-05-30)</td>
<td>1, 2, 4-11, 14, 15</td>
</tr>
<tr>
<td></td>
<td>paragraphs [0104] - [0109], [0120] ; figure 3</td>
<td>10-13</td>
</tr>
<tr>
<td></td>
<td>paragraphs [0148] - [0152] ; figure 6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>paragraphs [0171] - [0174] ; figure 8</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>US 7 808 128 B1 (WEBER JR JOHN ROBERT [US] ET AL) 5 October 2010 (2010-10-05)</td>
<td>1, 15</td>
</tr>
<tr>
<td></td>
<td>column 4, line 8 - column 5, line 28; figure 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>column 7, lines 34-67</td>
<td></td>
</tr>
</tbody>
</table>

[X] Further documents are listed in the continuation of Box C.  
[X] See patent family annex.

* Special categories of cited documents:

- "A" document defining the general state of the art which is not considered to be of particular relevance.
- "E" earlier application or patent but published on or after the international filing date.
- "L" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention.
- "X" document of particular relevance; the claimed invention cannot be considered without it in the inventive step when the document is taken alone.
- "Y" document of particular relevance; the claimed invention cannot be considered without it in an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- "A" document member of the same patent family.

Date of the actual completion of the international search: 5 May 2014

Date of mailing of the international search report: 13/05/2014

Name and mailing address of the ISA:

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer: Colombo, Al essandro

Form PCT/ISA2/010 (second sheet) (April 2005)
<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patent document cited in search report</td>
<td>Publication date</td>
<td>Patent family member(s)</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>-----------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>US 2013134779 AI</td>
<td>30-05-2013</td>
<td>JP 2013118804 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2013134779 AI</td>
</tr>
<tr>
<td>US 7808128 BI</td>
<td>05-10-2010</td>
<td>NONE</td>
</tr>
<tr>
<td>US 4319224 A</td>
<td>09-03-1982</td>
<td>CH 641610 A5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DE 2825240 AI</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FR 2434525 AI</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP S54162412 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 4319224 A</td>
</tr>
<tr>
<td>US 2006271313 AI</td>
<td>30-11-2006</td>
<td>NONE</td>
</tr>
</tbody>
</table>