Introduction to Empowerment with an Application in Control of Electrical Distribution Grids

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Abstract – Empowerment is an adaptive formalism which strives for an environmental state, where a local agent has the most options to act. It is universally and task-independently defined by the information theoretical channel capacity. In this paper, for the first time, the approach of Empowerment application to the control of electrical distribution grids is examined. Empowerment is applied successfully in a simulation of voltage control by altering active and reactive power. Further and more reasonable application areas could be the control by a probability distribution and dynamic and self-organizing systems.

1 Introduction

Artificial intelligence (AI) is a very popular topic in computer science and one goal of it is to enable an artificial agent to behave intelligent in a complex environment. One approach is to learn from a real world model and to implement the resulting strategy into the agent-behavior. In this case, a big set of data or a detailed model of the world is needed. Another approach could be a specific programmed solution to one particular problem. In this case, the agent solves the problem it is designed for in a specific manner. However, this behavior can lead to a non-optimal solution, due to a simplification of the problem or not considering all possible factors.

The approach considered in this paper differs fundamental to the former described approaches as it uses the quantity of *Empowerment*. This quantity rates the current agent's state in the world, following the heuristic 'the state providing the highest number of options is the most desirable'. Regarding this heuristic, an agent will always pursuit to a state where its number of options is maximized. This enables an agent to solve problems:

- Locally – it is not necessary to know the dynamics of the entire world, since the local dynamics of the agent are enough
- Universal – it is possible to apply *Empowerment* to every possible agent-world interaction
- Task-independent: it is possible to apply the formalism to any task as *Empowerment* is only determined by the agents' embodiment in the world and not evaluated regard to a specific goal or external reward (Salge et al., 2013).

Summarizing, *Empowerment* is defined by the information-theoretical approach of the maximum information flow (also known as channel capacity) between the taken actions of an agent and the impression of the environment. The main idea is to quantify the options of an agent to determine its influence in the world. Further, for the first time, Empowerment is introduced as an approach to control electrical power distribution grids.

In this paper we first introduce *Empowerment* and define the necessary information-theoretical notations. Then, we show the functionality of *Empowerment* in detail, using a simple grid world example. Finally, we apply *Empowerment* to a control problem in an electrical power distribution grid.

2 Empowerment

2.1 Motivation

Empowerment is driven by the behavior of animals. Predators, for example, are more successful, if their senses are more sensitive or if they are faster, stronger or more intelligent than their competitors. In other words an animal pursuits to gain more power and to have more options to influence the environment. This basic idea is fundamental to the *Empowerment* concept. Maximizing ones options in the world means to find the most powerful state, which might be the best state.

Transferred to an electrical power distribution grid this means the objective is to find a stable operation point which matches the boundaries of the environment and maximizes the power and security of supply. The control of electrical power distribution grids is very important as the supply by fluctuating power generators, like wind turbines and solar power plants, is increasing.

This issue is a proper application for the concept of *Empowerment*.

2.2 Definition

We consider the actual state of an agent in the world as the initial state. The *Empowerment* of an agent can be measured as the number of an agent's options to influence the environment. To determine an agent's influence a discrete memoryless channel, as shown in Figure 1, is considered (Ip, 1999). A discrete channel is consisting of an set of actions $\{a_1,\dots, a_v\}$, an resulting sensor set $\{s_1,\dots, s_w\}$ and a probability transition matrix $P_{i,j} = \{p(s_i|a_j)\}$ that gives the probability of observing state s_i when the action a_j was taken.

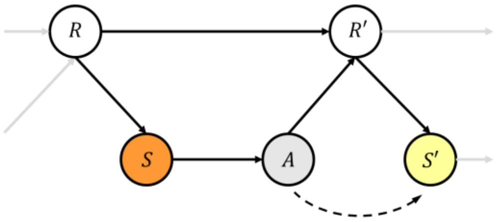

Figure 1: Causal Bayesian network of the perception-action loop, unrolled in time showing the sensor state set S and the action set A. The performed action has an influence on the world and how the sensor set S' perceives the environment R' and is described by an transition probability matrix (dashed arrow) (Salge et al, 2013).

The influence of an agent is defined as the mean amount of information. *Empowerment* is based on terms of information theory, it was first described by C.E. Shannon (Shannon, 1948). To understand *Empowerment* in detail, it is necessary to introduce several standard notations. Entropy is the average amount of information (Salge et al, 2013). For example, the entropy of the sensor set S is equal the mean amount of perceivable sensor states measured in bits.

$$H(S) = -\sum_{s \in S} p(s) \log_2 p(s)$$

Entropy is also described as the logarithm of all possible sensor outcomes described by the probability to perceive a state s of a set of states S. The conditional entropy is the information loss or remaining uncertainty, for example, of S when A is known. A describes a set of actions a that an agent can perform to alter its environment. The conditional entropy is higher if one single action leads to several sensor outputs, according to the environment as shown in Figure 2.

$$H(S|A) = -\sum_{a \in A} p(a) \sum_{s \in S} p(s|a) \log_2 p(s|a)$$

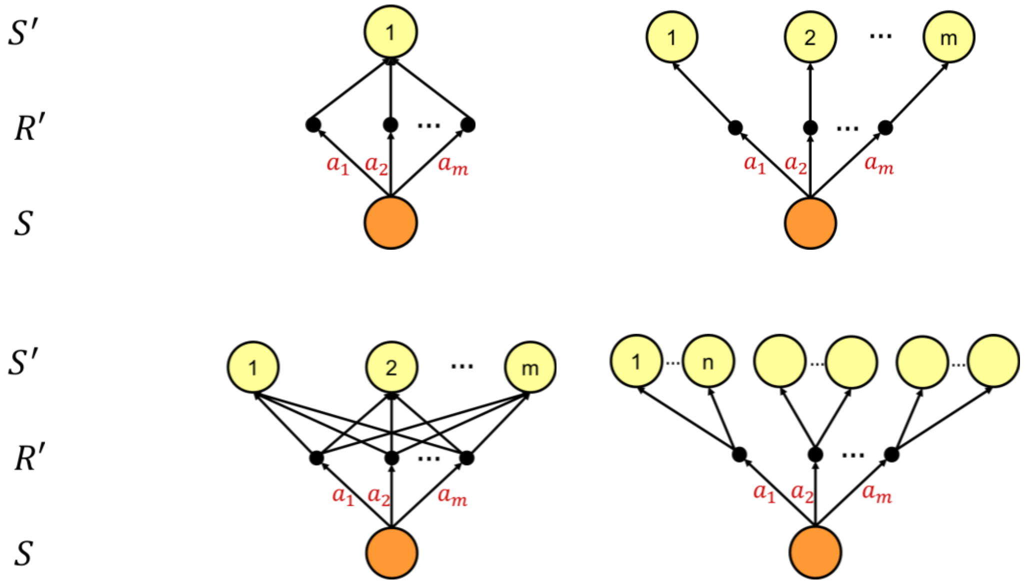

Figure 2: Illustrations of entropies and resulting *Empowerment*. S is defined as initial sensor set, $\{a_1,\dots, a_m\}$ as action set, R' as resulting environment set, S' as resulting sensor set.

(top,left) $H(S) = \log_2(1)$, $H(S|A) = 0$, $I(S{:}A) = 0$, $\mathfrak{E} = 0$

(top,right) $H(S) = \log_2(m)$, $H(S|A) = 0$, $I(S{:}A) = 0$, $\mathfrak{E} = \log_2 m$

(bottom,left) $H(S) = \log_2(m)$, $H(S|A) = \log_2 m$, $I(S{:}A) = 0$, $\mathfrak{E} = 0$

(bottom,right) $H(S) = \log_2(n \cdot m)$, $H(S|A) = \log_2 n$, $I(S{:}A) = \log_2 m$, $\mathfrak{E} = \log_2 m$

In Figure 2, several transition paths from one sensor state S via an action set A to another resulting sensor set S' are illustrated. The entropy of the sensor set is equal the resulting sensor states in bits. On the one hand, if an action lead to one explicit sensor state, the sensor uncertainty respectively conditional entropy is zero (Figure 2 (top)). On the other hand, if an action lead to several sensor sates a conditional entropy exist (Figure 2 (bottom)) and can even match the entropy of the sensor set (Figure 2 (bottom, left)). The difference of the entropy and conditional entropy is called mutual information and quantifies the average information flow one can perceive from one's own actions (Salge et al, 2013).

$$I(S{:}A) = H(S) - H(S|A)$$

$$I(S{:}A) = \sum_{j=1}^{v}\sum_{i=1}^{w} p(a_j) \cdot p(s_i\,|a_j) \cdot \log_2 \left\{\frac{p(s_i|a_j)}{\sum_{k=1}^{n} p(s_i|a_k) \cdot p(a_k)}\right\}$$

As stated by Shannon the channel capacity is the maximum information that can be reliably transmitted from action as output to sensor as input.

The *Empowerment* of an agent is equal to the channel capacity.

$$\mathfrak{E} = C(s) = \max_{p(a)} I(S{:}A)$$

Empowerment quantifies the maximum of mutual information over all action probabilities $p(a)$ and is therefore independent of the actions. It is only depending on the resulting sensor set S (Figure 2).

3 Experiments

In the following section we apply *Empowerment* to two different experiments to show the basic functionality and an approach of application to an electrical control problem.

3.1 Grid World

First, we apply *Empowerment* in a simple grid world. An agent is discretely mapped to a single cell at a given time t and able to perform five different actions (X – stay, move N – north, E – east, S – south, W – west). If a certain action is not possible (due to walls or world boundaries) one prime state may not be reached (Figure 3 *(right)*). To cover a higher state space one can use n-step *Empowerment*. 2-step *Empowerment* means the concatenation of two actions for example: after taking one particular action, all five actions will be performed again (Figure 3 *(left)*). This allows different paths to one prime state.

As shown in (Figure 3 *(left)*), 2-step *Empowerment* leads to a total of 13 prime states and a maximum *Empowerment* of $\log_2 13 = 3.7$ [bits] (given 25 different actions). The *Empowerment* in one point in the grid world can be calculated by the logarithm of the set of reachable states.

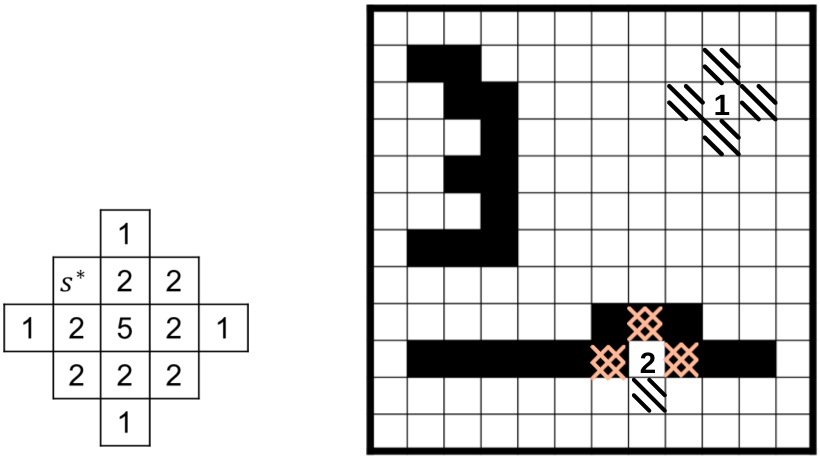

Figure 3:
(left) 2-step *Empowerment*: State s^* can be reached by moving first one step north then west or moving first west then north. The numbers in the figure represent the count of different paths leading to one particular state.
(right) 1-step *Empowerment* evaluation in two points. The agent performs the five different actions and can either reach a resulting cell (hatched) or not (crosshatched). It is not possible to access the walls (black cells) or exceed the world boundaries.
(Point 1) In this point of the grid world every action is possible and leads to a different prime state. This maximizes the *Empowerment* to $\log_2 5 = 2.37$
(Point 2) This point is surrounded by walls. Only the actions X – stay and S – move south are possible. Therefore the *Empowerment* is $\log_2 2 = 1$

The probability transition matrix for point 2 is shown in Table 1.

Table 1: Probability transition matrix for point 2 as initial state

Probability *P*	S'	Action
$p(s_X\|X) = 1$	s_1	X – stay
$p(s_N\|N) = 0$	s_2	N – move north
$p(s_E\|E) = 0$	s_3	E – move east
$p(s_S\|S) = 1$	s_4	S – move south
$p(s_W\|W) = 0$	s_5	W – move west
All other $p = 0$		

The *Empowerment* algorithm is applied to every discrete cell in the grid world the output is shown in Figure 4.

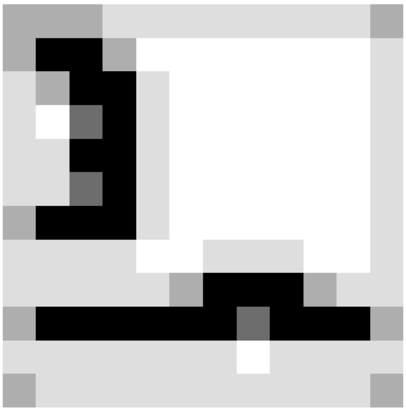

Figure 4: *Empowerment* map for 1-step *Empowerment*. The resulting *Empowerment* is between 1 (dark) and 2.32 bit (light). In areas with bigger distance to walls (black) the *Empowerment* is higher.

3.2 Application in Voltage Control of the Electrical Distribution Grid

Nowadays, the control of electrical distribution grids is an important issue, in particular in the context of *Energiewende* where we replace central fossil by distributed renewable power plants. Hence, increasingly more power is produced in the distribution grid, which often leads to a bidirectional power flow. Changes of the power flow direction lead to voltage fluctuations, which compromise the security of supply.

In Figure 5, a schematic layout of a renewable power plant connected to the distribution grid is shown.

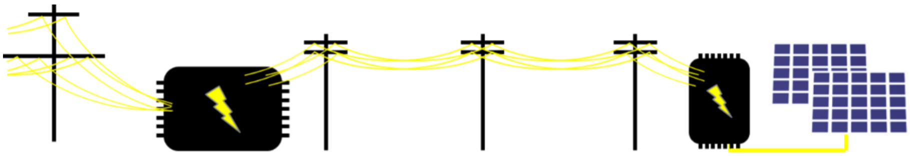

Figure 5: Schematic layout of the distribution grid (middle position) that relate via a transformer to the utility grid (left position) and is connected to a renewable power plant (PV cells and related converter, right position).

From an electrical engineering point of view, the considered system of Figure 5 consists of a fixed low-voltage grid and a simple power line with a particular resistance and inductance (Figure 6). For further simulations, a ten kilometer AC cable of VPE 4x150 SE and a nominal voltage of 230 Volt (low voltage grid) are assumed (Waffenschmidt, 2014).

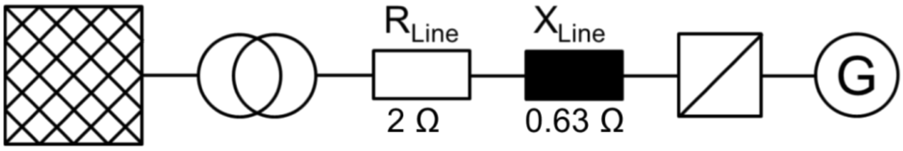

Figure 6: Equivalent network of the line of distribution grid (Resistance R_{Line}=2 Ω, inductive reactance X_{Line}=0.63 Ω, middle position) that relates via a transformer to a fixed grid (left position) and is connected to a renewable power plant (generator and related converter, right position).

At the end of the line, there is a distributed generator which feeds power into the grid. However, feeding power into the grid raises the local voltage level at generator side, so the voltage tolerance of ±10% of the nominal voltage is exceeded easily (Figure 7). In consequence, the distribution grid would be irreversibly damaged. To solve this issue, the grid infrastructure needs to be improved. To avoid the costs of a new grid infratructure, the problem can be solved by power factor adaption. The voltage level can be reduced by reducing active power or feeding additionally reactive power into the grid (Waffenschmidt, 2014).

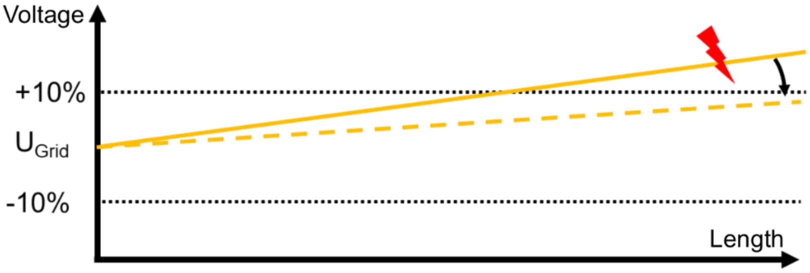

Figure 7: Exceedance of the voltage tolerance limits of ±10% of the nominal voltage at the grid location of the generator (right). The voltage level can be reduced by feeding additionally reactive power into the grid (dashed line).

In order to solve this problem by means of *Empowerment*, the reaction behavior of the power factor adaption system needs to be known. To define such a "world" function, we need to specify the electrical relations in greater detail.
In general, the generator has two degrees of freedom: active and reactive power (P_G and $\underline{Q_G}$). The complex generator power $\underline{S_G}$ is changed by means of the complex generator current $\underline{I_G}$, while the generator voltage U_G remains active:

$$\underline{S_G} = P_G + \underline{Q_G} = \underline{I_G} \cdot U_G$$

The principle of voltage ascent is displayed in Figure 8. To show the resistance and inductance of the power line, the voltage vectors are considered in a complex plane.

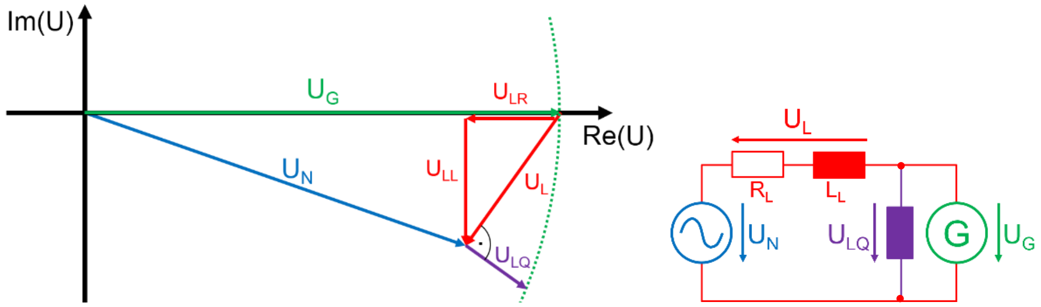

Figure 8: Voltages of the considered system including generator voltage U_G, nominal grid voltage U_N and line voltage U_L that consists of a resistive voltage U_{LR} and an inductive voltage U_{LL}. U_N and U_G can be adjusted by adding a parallel inductance with the complex voltage of U_{LQ}. Left: Relation of the vectors in the complex plane of voltage. Right: Considered voltages in the equivalent circuit of the system (Waffenschmidt, 2014).

According to Figure 8, the generator voltage U_G is higher than the nominal grid voltage U_N by the complex voltage drop in the power line U_L. To compensate the voltage ascent reactive power is fed into the grid. In Figure 8, this reactive power is featured by means of an additional parallel inductance. The voltage vector of the added inductance U_{LQ} is perpendicular to the line voltage U_L (Waffenschmidt, 2014).
In addition, the generator voltage U_G can be deduced from these figures:

$$U_N{}^2 = (U_G + U_{LR})^2 + U_{LL}{}^2 \;\; \Leftrightarrow \;\; U_G = \sqrt{U_N{}^2 - U_{LL}{}^2} - U_{LR}$$

The resistant and inductive voltage drop are defined by means of the complex generator current:

$$U_{LR} = R_L \cdot Re(I_G) - X_L \cdot Im(I_G)$$

$$U_{LL} = X_L \cdot Re(I_G) + R_L \cdot Im(I_G) \qquad \text{with } X_L = 2\pi \cdot f \cdot L_L$$

Thus, the "world" function of generator voltage U_G is described as:

$$U_G = \sqrt{U_N{}^2 - (X_L \cdot Re(I_G) + R_L \cdot Im(I_G))^2} - (R_L \cdot Re(I_G) - X_L \cdot Im(I_G))$$

Finally, the "world" function for power factor adaption can be shown in a complex plane of generator current $\underline{I_G}$. In Figure 9, the function of complex current is shown, where the generator voltage comply with the nominal grid voltage (230 V). The grey area displays the allowed voltage tolerance of ±10% of the nominal grid voltage (VDE-AR-N 4105, 2012).

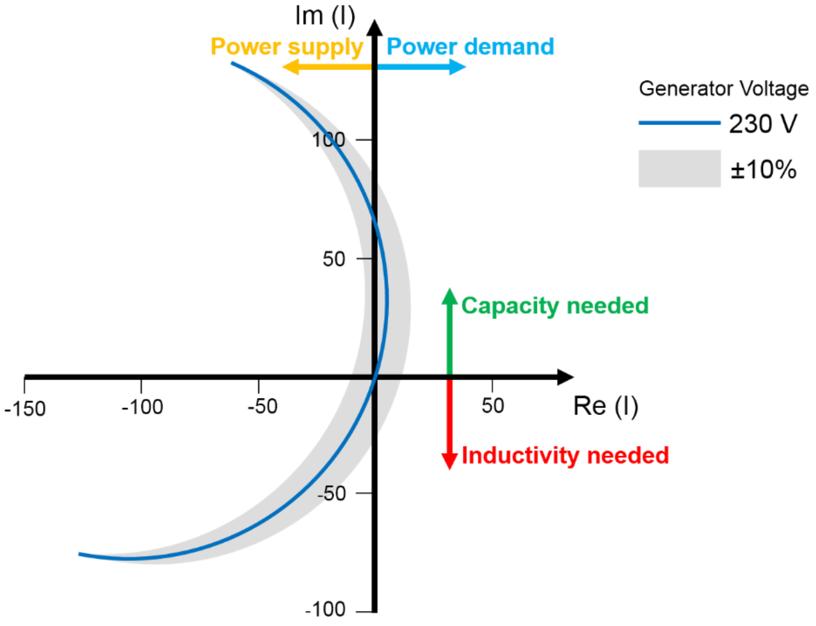

Figure 9: „World“ function of power factor adaption in the complex plane of generator current $\underline{I}_G$. Shown is the function line of complex generator current complying with nominal grid voltage U_N=230 V within the allowed voltage tolerance limits of ±10% of the nominal grid voltage (grey area). Positive active current means a power demand respectively negative active current a power supply. For positive reactive current a capacity and for negative current an inductivity would be needed.

Furthermore, the *Empowerment* approach will be applied to solve the optimal operational points for this “world” function to ensure the highest system stability.
In order to determine the local *Empowerment*, the algorithm evaluates every position in the sickle shaped world (Figure 10). For purposes of presentation, in this figure a 2-step Empowerment is applied.

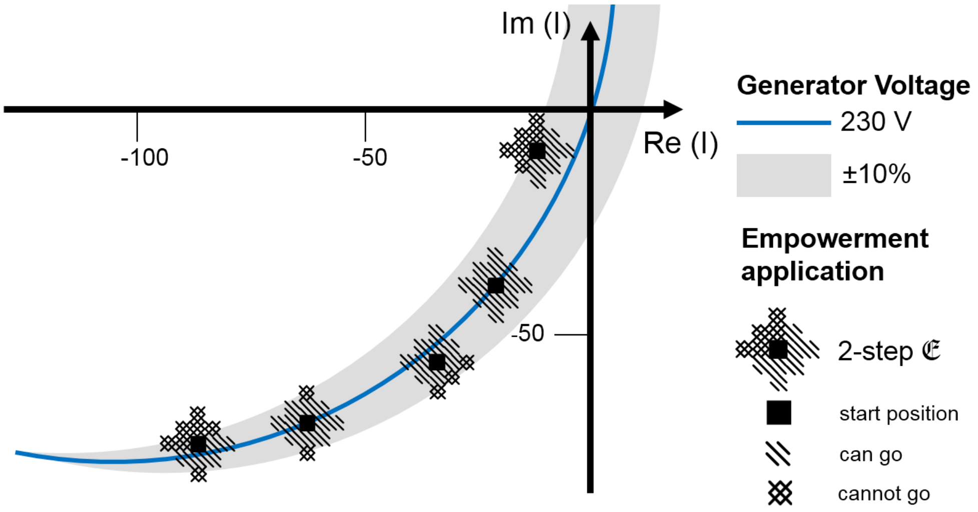

Figure 10: *Empowerment* application to the “world” function. Evaluation of *Empowerment* algorithm to every position in the system. Exemplarily shown evaluations with start position (black), where the agent can go (hatched) and where he cannot go (cross-hatched).

The simulation result for a 10-step Empowerment is shown in Figure 11. The heat map displays the empowerment value in bits for every starting positions in the sickle-shaped world.

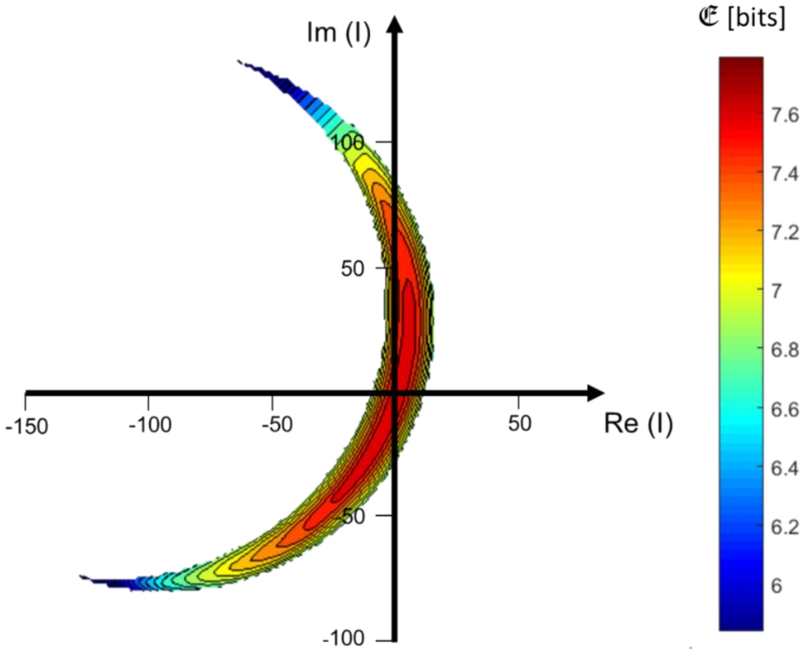

Figure 11: Heat map of *Empowerment* quantity 𝕰 [bits] by means of a 10-step *Empowerment*.

The *Empowerment* of an agent correlates with the shortest distance to a boundary, so the highest Empowerment is reached in the center of the broadest position of the sickle world. In addition, the *Empowerment* value gets lower the greater the generated active current respectively power is (negative direction of Re(I)).

4 Discussion of the Results

Finally, the *Empowerment* formalism is, for the first time, applied to a more complex physical problem like the control of electrical distribution grids.

According to Figure 11, high *Empowerment* values occur only on operational points of low active current. In this case, *Empowerment* would compete with the highest possible power supply of the generator. Nevertheless, assuming the grid voltage fluctuates, the *Empowerment* could indicate the operational security. During shifting of the grid voltage, an operational point with low *Empowerment* would exceed the allowed voltage tolerance limits much earlier than a point with high *Empowerment*.

5 Conclusion and Perspective

In summary, *Empowerment* is an adaptive formalism based on performing a local perception action loop. Furthermore, it is universally and task-independently described by the information theoretical term of channel capacity.

The application proposal of electrical grid control works so simple it could also solved by means of a linear regulator.

A further more complex research area for an *Empowerment* application is the control by blurred limits. For example, diesel generators often have to run at a minimum partial load of 50% to avoid damages in long-term. However, they are able to reduce its power under 50% of partial load for a limited time period without getting damaged. In a PV-Diesel hybrid generator system, the minimum of diesel power could be further decreased by defining blurred limits by probability distributions.

Another attractive issue is the investigation how *Empowerment* works in multi-agent or high dynamic systems. Previous research discovered that *Empowerment* autonomously structures a multi-agent group similar to swarms (Capdepuy, 2010). For example, to distribute the electrical grid control to local agents could simplify the initial connection of distributed generators in the plug-and-play manner.

References

Capdepuy, P., “Informational principles of Perception-action loops and collective behaviours”, doctoral thesis, University of Hertfordshire, 2010

Ip, L, “The Blahut-Arimoto Algorithm for the Calculation of the Capacity of a Discrete Memoryless Channel”, University of California, 1999

Jung, T., Polani, D., Stone, P., Empowerment for continuous agent-environment systems. Presentation at GSO Workshop, University of Hertfordshire, 2011

Klyubin, A. S., Polani, D., Nehaniv, C., “All Else Being Equal Be Empowered”, University of Hertfordshire, 2005

Salge, C., Glackin, G., Polani, D., “Empowerment – An introduction”, University of Hertfordshire, 2013

Shannon, C., “A mathematical theory of communication”, Bell Syst. Tech. J., 1948

VDE-AR-N 4105, “Power generation systems connected to the low-voltage distribution network - Technical minimum requirements for the connection to and parallel operation with low-voltage distribution networks”, Application rule, valid and binding from January 1st, 2012

Waffenschmidt, E., “Electric grids - Lecture notes”, 2014

Waffenschmidt, E., “Decentralized structures of electric grids - Lecture notes”, 2015