Energy Coupling Control of Telecommunication Network and Power Grid

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***Abstract*—In this paper, we present a control architecture that allows to operate the energy storage facilities integrated into the wide area telecommunication network as mediators between the optimality criteria of the *Smart Grid* and the energy consumption modeling of the telecommunication network itself. Different control modes are discussed.**

Keywords—Green ICT, Smart Grid, energy storage facilities, telecommunication network

I. Introduction

In this paper, it will be argued that the storage facilities for electrical energy which have been integrated into the national carrier networks as a power reserve for blackouts with system-wide coverage may serve as a crucial link between the telecommunication network domain and the emerging *Smart Power Grid* (for an – albeit not rigorous – definition and basic discussion see [1]).

Consider the following three-part reasoning, first seen from the energy domain point of view:

- The success of the so-called *Smart Grid* will hinge on its capability to incorporate renewable energy sources on a large scale.
- The renewable energy sources (mainly wind and solar energy) come with a high volatility – time and place of their availability will, as a rule, not coincide with the demand.
- Hence, technically efficient and controllable energy storage topologies with a system-wide coverage have to be set up.
- (Also, concurrent transmission network capabilities have to be created. For the argument of the present paper, this aspect shall be disregarded.)

On the other hand, the national carrier telecommunication networks such as e.g. *Deutsche Telekom* (DT) in Germany are heavy consumers of electrical energy (German landline operation of DT alone consumes around 2 TWh per year). As the traffic load of network services increases in near-exponential fashion (e.g. [2]), to curb the energy consumption in all layers of the ICT (information and communication technology) domain is a paramount task for the ICT industry, summed up in the term *Green ICT*. The reasoning given above is now met by the ICT domain point of view:

- Emergency electricity provisioning has historically been integrated into the telecommunication network at each of the major technology sites (approximately 9.000 in the case of DT) and further real estate sites.
- Whereas at a share of these sites performance is individually measured with a high temporal resolution, others are provisioned according to suitable standard load profiles.
- The actual technology is a lead-acid storage battery with a summed-up capacity of ca. 22 MAh. This value is, at closer inspection, a nonlinear function of the discharge current.
- As per current operation, the default charge level is 100%.

The conclusion is fairly simply to draw: provided the option of remote management is given for the storage batteries, their charge levels can now be regarded as control entities with two competing control paradigms:

A. *Telecommunication Consumption Modelling*

The storage capacity is used to cap peak loads of the telecommunication network energy demand and shift them to off-peak times. As the spot market prices of electrical energy (day-ahead trading) are strongly correlated to the aggregate load profile, even minor shifts of peak loads result in reductions of the overall power bill. Further optimization dimensions are the transmission fees which are a strongly nonlinear function of site-specific performance values and controllable variations of the standard load profile. This is a purely Telco-internal optimization scenario.

B. Smart Grid *Stabilization Services*

Alternatively, the buffer control can be operated according to the necessities of the utilities: positive and negative control energy options could be realized, or, storage elements may be operated as parts of virtual power plants. The remuneration in this control paradigm is external and is derived from the economical value of the *Smart Grid* stabilization.

Both paradigms may, however, be combined. With a common value scale (e.g. currency units), a joint cost function can be constructed comprising the values of *Smart Grid* stabilization services *and* power purchase bill reductions. The mathematics of complex optimization allows, then, to identify the optimal operation of the storage elements with respect to the two domains *"Smart Grid"* and *"Green ICT"*.

This work reports first findings on the presented control mechanisms derived from research at Deutsche Telekom

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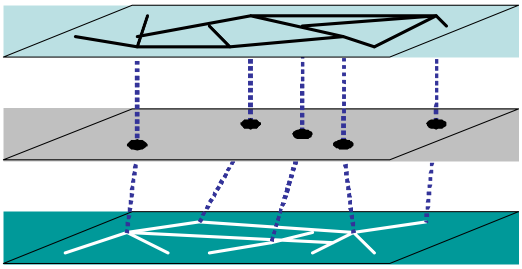
Laboratories and discusses the possible further developments.

The paper is organized as follows: in the first section, the joint control architecture of the coupled domains *"Smart Grid"* and *"Green ICT"* is developed and discussed. In the second section, partial optimization scenarios for the operation of the energy buffers are developed and recent R&D work (at DT) is scanned for relevant input. A synthesis is subsequently developed. Finally, an outlook is given.

II. Joint Control Architecture and Control Parameters

In Figure 1, the layer coupling as described above is schematically depicted. In the topmost layer, the network structure of energy consumption in the telecommunication domain is shown. The energy buffer elements integrated in this network constitute the mediating middle layer, whereas the bottom layer represents the power grid.



$$P_{tel}(x,t) = P_{tel}^{(0)}(x,t) + V\partial_t \eta_{buffer}^{tel}(x,t)$$

$$\eta_{buffer}(x,t)$$

$$P_{grid}(x,t) = P_{grid}^{(0)}(x,t) + V\partial_t \eta_{buffer}^{grid}(x,t)$$

Figure 1: Telecommunication and electrical power network coupled by energy buffer elements.

The coupling function η is a capacity measured in Ah. Its first temporal derivative gives a current which describes charging and discharging of the buffers. Multiplied by the voltage a positive or negative performance is expressed which might be operated to modify the performance balance in the top and bottom layer. Several observations are due:

- In the telecommunication network no energy is generated. Therefore, $\partial_t \eta_{buffer}^{tel} \leq 0$ at all times.
- A cyclical recharging boundary condition is implemented: $\eta(t) = \eta(t+T)$ with $T = 24$ h as the starting point.
- Discharge current limitations are derived from the battery technology: $|\partial_t \eta_{buffer}| \leq I^*$ in order to preserve the nominal capacity and ensure the life expectancy of the battery.
- Note also the basic dimensioning $P_{tel} \approx 0.02 \times P_{grid}$.

Let us now shortly discuss Figure 1. In the top layer, the buffered performance of the telecommunication network as presented to the grid is expressed as the sum of the unmediated consumption $P_{tel}^{(0)}$ and the buffer performance. The latter is always negative as energy can – in this layer – only be taken out of the buffers. $\partial_t \eta_{buffer}^{tel}$ presents thus a means to react to price variations as it dissolves the rigid coupling between consumption and grid-based provisioning.

In the mediating middle layer, the buffer charge $\eta_{buffer} = \eta_{buffer}^{tel} + \eta_{buffer}^{grid}$ is here modeled to consist of two parts – one mediating the telecommunication network consumption and one interacting with the grid itself. The latter describes the purchase of buffer energy in off-peak hours ($\partial_t \eta_{buffer}^{grid} \geq 0$) as well as technoeconomical operations typical for the *Smart Grid*. The most important of these are:

- Positive control energy: Buffer energy is fed into the grid in order to counteract under-provisioning ($\partial_t \eta_{buffer}^{grid} < 0$). The corresponding economics is usually a traded option over a specified amount of energy with defined performance. The use of distributed medium-sized buffers prevents the costly use of control power plants, e.g. gas turbines and is very efficient with respect to transport costs.
- Negative control energy: Buffer capacity is offered to be charged with surplus energy which threatens to destabilize the transmission grid. The typical situation is a high feed of wind energy in night hours not met by comparable consumption. Again, options to charge buffers are traded as a reassurance against grid destabilization. As above, the system-wide coverage of buffers allows to act in the lower hierarchy layers of the grid, thus transferring – and effectively curbing – risks from the high-voltage grid to medium-and low-voltage parts.
- Virtual power plants: Physically the same effect as the positive control energy discussed above, the coupling of buffer performance into a cloud of generation facilities constitutes a virtual power plant. The mode of operations, however, will be different: option trading with rare actual events is replaced by regular operation. Lifecycle considerations have, thus, to be taken into account.

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III. Buffer Operation Control

In this section, first approaches to the control paradigms presented above are reviewed and discussed. Before embarking on the full systemic case, let us consider the decoupled regimes $\eta_{\text{buffer}}^{y} = 0$, where y = {tel, grid}, respectively.

A. *Telecommunication Consumption Modelling*

Following the reasoning given in the introduction, research activities at T-Labs, the central R&D department of Deutsche Telekom Group, have been set up to investigate the use of buffers in the pure y = tel mode discussed above. Starting point is an energy provisioning mode where the bulk of energy is secured by long-term base and peak contracts. This results in a rectangular function which has to be shaped by day-ahead trading on the stock exchange to the actual demand function. Only this latter part of the overall provisioning is subject to the buffer mediation as discussed in this paper since for long-term effects the buffer size is not sufficient.

In a detailed analysis of historical data (consumption data and stock exchange prices of the years 2008 and 2009), the feasibility of buffer operation to model the Telco network consumption has been studied. Two effects have been shown to dominate the optimization:

- Balancing group management: The stock exchange price curve (see Figure 2) gives clear indication at what times purchase should be avoided and at what times encouraged.

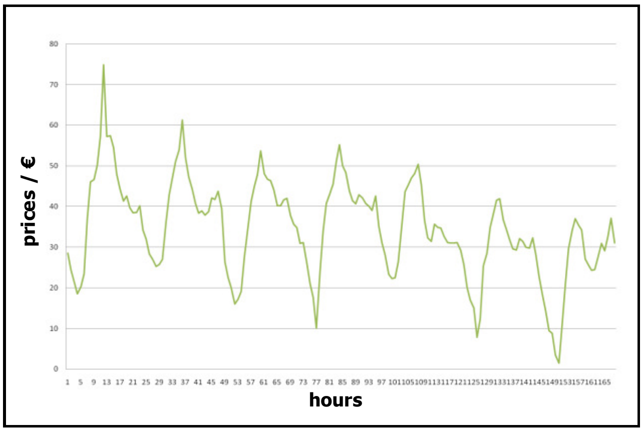

Figure 2: Exemplary stock exchange prices over a week, beginning with Monday. Night times, especially at the weekend lead to zero, even negative prices.

- Transmission fee optimization: transmission fees are built on the basis of the maximal current integrated over any 15 minutes in the course of a year. Uncontrolled buffer recharging, e.g. after a maintenance operation or an actual black-out incidence, leads to high transmission bills. This effect cannot be studied in the aggregate model developed in the initial analytics approach since the consumption sites have individual characteristics and have to be modeled individually.

In a first evaluation, perfect a priori knowledge about stock exchange prices has been assumed (given by the historical data). Also, operational issues of the battery management have been neglected (lifecycle issues, current limitations etc.). Then, the optimal buffer operation has been determined by linear optimization. The result is given in Figure 3 [3] .

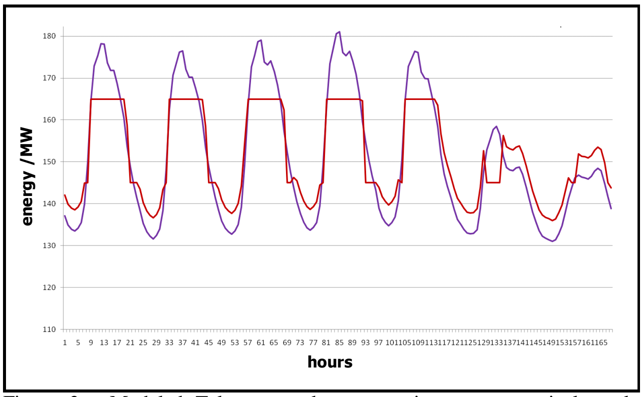

Figure 3: Modeled Telco network consumption over a typical week beginning with Monday: The red curve shows how the load peaks are capped by buffer energy.

Figure 3 shows how the load peaks of the Telco network consumption can be capped by $\partial_t \eta_{\text{buffer}}^{\text{tel}}$: Charging at night and weekend times enables the aggregate buffer (note again: this is a model pathology) to substitute the peak loads over the working week.

B. Smart Grid *Stabilization Services*

In this subsection the pure y = grid mode – as introduced in the beginning of section III – and the related use of the buffers is elaborated on.

In *Smart Grid* environments several types of energy have to be integrated and handled within an overall electricity grid: Besides the energy generated by conventional power plants like coal-burning power plants or nuclear power plants renewable energies have to be included. Typical renewable energy sources are wind, sun and tides, but also for example biomass. Renewable energy is highly volatile with respect to time t and location x of its occurrence in a power grid – and the amount of renewable energy generation is thus a function of time t and location x. Wind energy is typically generated in certain regions – e.g. in maritime regions by using on-shore facilities and in off-shore wind parks, where strong wind activity is observed. The wind occurrence and intensity has a statistical nature [4] leading to a high variation in wind output with respect to time and locality. Solar energy is best generated in regions with long periods and high probability of sunshine. These areas may be preferably desert-like regions which are – in general – different from regions with high wind output. Tidal energy sources depend on tidal flows in the sea. They are expected to be better predictable with respect to temporal occurrence [4], but this type of energy is restricted to sea shores with significant tidal activity. Some

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congruence between the wind and tidal energy source locations may be argued, but also in these cases there may be significant discrepancies since high wind capacity is not only observed in maritime and off-shore regions, but also in central country parts [4]. Another renewable energy source is bioenergy for future energy supply where a major challenges lies in its sustainable and efficient use and generation [5].

The time periods of interest are expected to range from short times, like diurnal or weekly periodicity, up to yearly and seasonal variability: An example would be the more strong wind activity in maritime regions during autumn and spring compared to typical summer winds – where instead the solar energy generation is expected to have a peak value with respect to historical observations.

The associated overall generated power $P_{grid}^{(0)}$ may be modeled as a function of time t and location x:

$$P_{grid}^{(0)}(x,t) = P_{coal}(x,t) + P_{nucl}(x,t) + P_{wind}(x,t) + P_{sun}(x,t) + P_{tide}(x,t)$$

Since the renewable energy sources generate a highly volatile power, the remaining conventional power plants will have to be able to provide a varying electricity demand – depending on the wind, sun and tide activity: Considering an exemplary case of a power consumer with approximately constant power draw – like, for example, current telecommunication networks within certain limits are – the electricity demand remaining for the coal-burning and nuclear power plants will vary and there is a need of energy storage to accommodate this in an efficient way.

Energy storage facilities are installed in electricity grids: As an example there are the pumped storage plants in mountainous regions which are able to store energy in mechanical form and convert them back to electricity on demand. However, the high volatility of renewable energy with respect to time and location will require, first, energy storage facilities which are able to handle requests in short times for storing and providing energy as well as, second, distributed storage facilities with sufficient capacity in a certain region to accommodate the location dependency of renewable energy generation. During times of generation of high amounts of renewable energy it will be necessary to store considerable amounts, but being able to deliver it during times of low activity of renewable energy sources. Central storage facilities, connected to e.g. geographical characteristics – like pumped storage plants are – may be not sufficient, since in that case possibly long distances would have to be bridged and the transmission loss would decrease the energy efficiency. Here a clear argument for de-centralized storage facilities is observed, since transmission losses can be minimized by distributed storage energy facilities. In conclusion of this paragraph it can be stated that current energy storage facilities are not flexible enough to handle the future grid requirements and hence more suitable solutions are necessary allowing for a more economical grid operation.

For the future it is expected that the share of renewable energies in the overall energy mix will increase targeting at a reduced greenhouse gas emission. For example in Germany there is the target established to have 35 % of the gross energy consumption generated by renewable energy sources by 2020 [5]. After that time, Germany targets at 50 % by 2030, 65 % by 2040 and 80 % by 2050 of gross energy consumption generated from renewable energy sources [5]. With respect to the longer term future, like e.g. looking at 2050 it is expected that wind energy will play a key role in electricity generation [5].

Before this background it will be necessary to establish concepts like those elaborated on in this paper to allow for an efficient and reliable energy supply by future electricity grids. The energy storage elements of the telecommunications network are distributed all over the country and have a certain capacity – which is usually much lower than the grid would require to accommodate the whole amount of variations. However, the distributed energy storage facilities may help to stabilize the grid and ensure its economical operation in cases of small variations of the provided grid power with respect to the power demand.

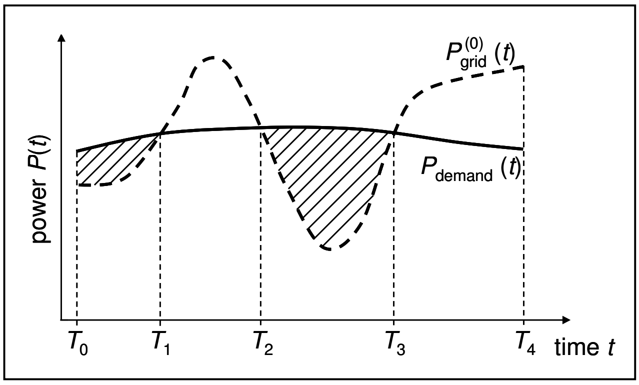

Figure 4: Exemplary and principle curves of the the power demand $P_{demand}(t)$ and of the grid-provided power $P_{grid}^{(0)}(t)$ over time t at a constant location x.

Figure 4 shows the principal behaviour of the generated power $P_{grid}(t)$ by the grid and the power $P_{demand}(t)$ demanded by the consumers as exemplary functions of time t, i.e. for a certain location (x = const.). The electricity demand $P_{demand}(t)$ is assumed to be nearly constant over time. Two cases concerning the buffer usage can be distinguished: Energy stored in the buffers is fed into the grid in order to counteract under-provisioning ($\partial_t \eta_{buffer}^{grid} < 0$) or the grid produces more power than demanded by the consumers and this surplus energy amount is stored in the buffers ($\partial_t \eta_{buffer}^{grid} > 0$). In Figure 4 this is illustrated: There are shaded areas – between T_0 and T_1 as well as between T_2 and T_3 – where $P_{grid}(t) < P_{demand}(t)$ ($\partial_t \eta_{buffer}^{grid} < 0$): In this case the grid generates less power than demanded by the power consumer, for example since there is low wind energy output. Then the difference power $P_{demand}(t) - P_{grid}(t)$ has to be provided by the energy storage facilities of the network, i.e. the batteries which had to be previously charged appropriately. During times, where $P_{grid}(t) > P_{demand}(t)$ ($\partial_t \eta_{buffer}^{grid} > 0$) – i.e. between T_1 and T_2 as well as between T_3 and T_4 – the batteries may serve as buffers and store the power generated, but not used by the

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power consumers at that particular time period. These amounts of energy than may be used at later points in time, when the first case applies.

C. Synthesis

Let us now sketch the combined control of Telco network energy consumption modeling and *Smart Grid* stabilization services. In the modeling language developed above in section II, a unifying cost function has now to be developed. In continuation of earlier work where the essential coupling mechanisms between layers have been modeled qualitatively [6], here, a more analytical approach is sought. To this end, the performance modeling of Figure 1 has to be set in relation to real costs.

Consider the performance-related costs as a functional (in arbitrary dimensionless units) of the overall buffer charge $\eta_{\text{buffer}}(t)$:

$$C[\eta_{\text{buffer}}] = \int \mathrm{d}t\, \pi_{\text{bm}}^{(0)}(t)\, \eta'^{2}_{\text{buffer}}(t) + \pi_{\text{c}} \eta_{\text{buffer}}(t). \qquad (1)$$

Here, the first rhs term describes the costs of the balancing group management: the stock exchange price function $\pi_{\text{bm}}^{(0)}(t)$ weights the charging and discharging performance, respectively. As discussed above, a further dependence of the costs on the charge and discharge currents exists (transmission fees) whence a quadratic dependence on the currents follows.

In the oversimplified model presented here, the positive control energy (see discussion above) may be regarded as subsumed in the balancing group management, since the corresponding option prices will strongly correlate with the stock exchange prices, so that $\pi_{\text{bm}}^{(0)}(t)$ may be understood as incorporating both.

The negative control energy costs, however, have to be modeled separately. This is done in the second term in eqn. 1: If π_{c} is a constant option price for providing negative control energy, the costs are directly proportional to the available buffer. It has to be stressed again at this point, that this model is not designed for mathematical accuracy but for highlighting the leading effects in the presented control problem. The Euler equation for the optimization problem (1) follows immediately to

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[2\eta'_{\text{buffer}}(t)\pi_{\text{bm}}^{(0)}(t)\right] = \pi_{\text{c}} \qquad (2)$$

Figure 5 shows the principal effects of the optimization problem (2): The higher the option price π_{c}, the more favourable it is to discharge the buffers since this creates capacity for accommodating the surplus energy (see above). In Figure 5, $\pi_{\text{bm}}^{(0)}$ has been modeled as a Gaussian centered at midday – in the rough modeling presented here, this mimics the realistic curve in Figure 2.

Obviously, a realistic negative control energy option price would reflect the higher risk of network instabilities due to overfeeding in the night hours. Also, correlations between stock exchange prices $\pi_{\text{bm}}^{(0)}$ and the aggregate load profiles which will also strongly influence both control energy prices have been neglected here.

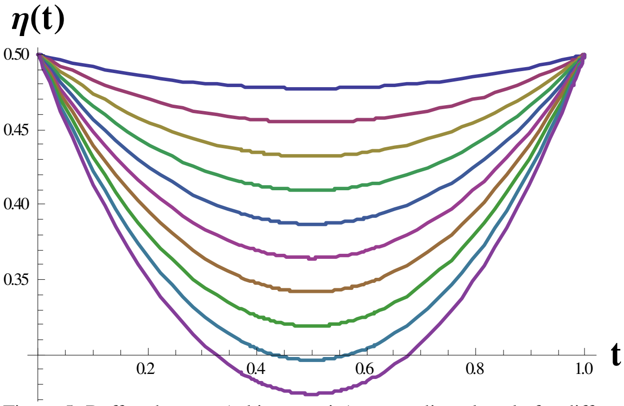

Figure 5: Buffer charge η (arbitrary units) over a diurnal cycle for different values of negative control energy option prices (increasing values from top to bottom).

In current R&D work at Deutsche Telekom Laboratories, a detailed spatio-temporally resolved model is developed in order to realistically gauge the effects presented here qualitatively.

IV. CONCLUSIONS AND OUTLOOK

In conclusion of the presented joint control approach of Telco network consumption modeling and *Smart Grid* effects, several principal findings can be stated:

- First, the gross demand and supply of electrical energy are coupled by prices – be that the stock exchange prices for day-ahead provisioning or the hedging prices for control energy of either sign.
- Further, a system-wide buffer structure integrated into the Telco network may be used in two different modes: either to model proprietarily the Telco consumption characteristics by load-shifting, or, to mediate performance surpluses and deficits of the *Smart Grid* itself.
- Thus, with integrated prices as a unifying basis, a cost functional can be derived for combining the different control requirements on the operation of the buffer charges integrated into the Telco network.

With respect to the behaviour of the combined control strategy, interesting options open up:

- There is mutual competition and enhancement of cost effects: Whereas negative control energy and balancing group management both act towards buffer discharge, positive control energy and Telco network consumption modeling compete. Here, a more refined model is needed to derive the optimal control strategy.
- Current initiatives for load-adaptive mode in the Telco network operation (see section III B and e.g. [6]) will amplify the presented effects: Whereas today the Telco network energy consumption varies little over time (see Figure 4), load-adaptive mode will correlate it more strongly with the general

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demand curve and, thus, the price curve. The buffering effects are expected to increase in scale for such a scenario.

- Furthermore, load-adaptive mode of the Telco network operation, turns the initially unresponsive $P_{\mathrm{tel}}^{(0)}(t)$ into a controllable entity. Thus, new options for stabilizing the *Smart Grid* arise.

For a working real-time control strategy, the stochastic character of prices and the renewable energy grid feed has to be taken into account. Furthermore, the model has to be broken down to the individual operation of the different buffer elements.

The principal argument of the presented work is that the energy elements integrated into the telecommunication carrier network may serve as a catalyst in *Smart Grid* evolution scenarios. As imperfect as sites and technology of today's energy buffers may be, they provide a relevant starting point by their system-wide coverage.

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