Journal of Energy and Power Engineering 9 (2015) 905-911
doi: 10.17265/1934-8975/2015.010.009

Smart Meters and Under-Frequency Load Shedding

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Received: August 24, 2015 / Accepted: September 14, 2015 / Published: October 31, 2015.

Abstract: In some countries, there exists a risk of power deficit in the EPS (electrical power system). This is a very serious problem and there are various solutions to deal with it. A power deficit in the EPS leads to frequency decrease in the power system. A dedicated automation to load shedding is used to maintain proper EPS operation. For some time, it has applied a mechanism called demand-side response, which in case of an emergency situation allows for a "more civilized" rationing of electricity to customers, with their consent. Such programs require that the utilities pay the customers for their agreement. The author proposes a new solution, intermediate between strict ALS (acting relieving automation) and demand-side response programs, where the companies have to send information about the price of energy or control signals to households.

Key words: Smart meter, smart grid, under-frequency, load shedding, electric power system.

Nomenclature

ALS	automatic load shedding
AMI	advanced metering infrastructure
AMR	automated meters reading
CPP	critical peak pricing
DLC	direct load control
DSO	distribution system operator
DSR	demand-side response
EPS	electric power system
HAN	home area network
ICR	interruptible/curtailable rates
ICT	information and communications technology
IHD	in-home display
LFC	load frequency control
RTP	real-time pricing
ToU	time-of-use pricing
TSO	transmission system operator
WAN	wide area network
$<f$	under-frequency
f_N	nominal frequency

1. Introduction

In some countries, there is a risk of power deficit in the EPS (electric power system). This is a very serious problem and there are various solutions that deal with this problem. A power deficit in the system leads to frequency decrease. Many years ago, preventive ALS (automatic load shedding) was developed. If the measurements indicate a frequency drop it automatically executes load decreasing. An automatic load shedding is categorized as one of the protection systems applied to the EPS.

Such automation is however a bad solution. Firstly, it usually completely shuts off the power to certain recipients, without their knowledge or consent. Secondly, it does not allow recipients to make selection which appliances could be shut off of power and those, that should still be supplied. Therefore, they have begun to use more civilized methods of energy rationing, in case of power deficit in the EPS. This is how demand-side response was developed, which, among others enables to perform certain rationing actions of energy supplies, with the consent of the end-users.

2. Power Balance and the Frequency

A balance between production and consumption of power at any given moment of time is indicated by the

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frequency of the power grid. In the steady state, power generated in power plants is equal to the power consumed by the end-users, plus transmission losses. In this situation, generator rotors rotate at a constant angular speed ω. If there is no power deficit in the power system, the frequency of the network in steady state is equal to the nominal frequency f_N, which is equal in Poland to $f_N = 50$ Hz.

Today, there is utilized a central frequency regulation in the power system. One common secondary frequency regulator is installed at the system operator plant. In case of a drop in grid frequency, the information about the drop is redirected to the central frequency regulator and this regulator takes actions to restore the nominal frequency of the power grid.

The increase in total active power demand causes grid frequency drop (generators speed), while the decrease in power consumption causes increase in the frequency. In the event of a change in power consumption, in order to maintain the system frequency within certain limits, a change in the amount of energy produced by generators or the amount of energy delivered to the power grid has to be made. In case of reduction of the power consumption by the customers, one can easily reduce the power supplied to the network through power stations. A problem may occur in situations of increased power demand. In such cases, it is necessary to start-up additional generators, which have a finite maximum power and cannot give more power into the power system. If there is no possibility of mobilizing additional generation capacity to maintain system stability and maintaining the frequency within certain limits, then load reduction is carried out.

If there will occur an increase in power demand and the power generation unit reaches its maximum power at the primary control, then it ceases to participate in the further adjustment of the frequency. In this case, its droop regulation becomes infinitely large, while the inclination of the frequency is equal to zero. In the event, when all power units will reach their maximum power capacity, the only possible response of the power system to the frequency reduction is to reduce the power load, depending on its frequency characteristic. To avoid such situation the power systems are using the spinning reserve, whose task is to ensure a proper operation of the primary frequency control.

It is worth noting that, the frequency drop is not a good indicator of a situation in the EPS. The frequency decreases when the system is overloaded or when adverse situations are already taking place. Dedicated automation does not affect the cause of the failure and it does not inform about the risk of its occurrence. Therefore, scientists and power engineers are looking for other indicators, which would determine the condition of the power system.

3. DSR (Demand-Side Response) Programs and Overload Protection

An implementation of many new DSR programs will be possible after the implementation of smart metering.

Such DSR programs, which are based on price signals, i.e., tariffs: ToU (time-of-use) and RTP (real-time pricing) cannot be used in real-time for security power system protection. These mechanisms are rather tools for shaping demand for energy in the long term. Thanks to them, some part of the energy consumption in residential sector is shifted to later periods (or reduced) from peak to off-peak hours [1-4].

Only the stimulus programs DSR, such as: ICR (interruptible/curtailable rates) and DLC (direct load control), whose use is associated with real possibility of partial reduction of energy consumption and load control by the network operator can contribute, in a real-time, to protect the power system from overloading.

A smart meter can directly control the household appliances. You can also find solutions, which assume sending of control signals through the smart meter into the HAN (home area network) controller. This controller controls the work of intelligent home appliances, based on the received information about the current time zone or based on the current energy prices [5]. A control signal could be sent by:

- the TSO (transmission system operator), in an emergency situation or in case of an power system overload;
- the supplier of energy, in case of high energy prices on the wholesale market.

Disadvantages of this solution are as follows:

- Sending price signals, e.g., to a smart meter or HAN controller, on a continuous basis, is inefficient, because a typical person sleeps 8 h a night, works 8 h a day, spends 2 h on his way to and from work in addition to leaving the house (shopping, meetings, walking) or is focused on performing certain actions: watching TV, reading a book, working on the computer;
- Price, control or shut off signals may not arrive to the destination or may be accidentally or intentionally misrepresented;
- There is room left for abuse, energy supplier may send a signal to shut down loads in a situation where the price of electricity on the wholesale market is high, but when there is no need to relieve the power system. However, if the energy supplier has reserved such a right in the agreement so that it can proceeded, it may seem to be a legitimate action;
- Processing of large amounts of data, supervision of distribution and transmission systems, sending price or control signals in real time, translates into significant additional power consumption by the communication and control systems.

Devices and functionality that can be used to optimize energy consumption:

- a smart energy meter with functionalities: reduction of maximum power in "emergency" state, the ability to remotely shut off the end-customer's power, the possibility of tariff changes;
- a HAN controller: to control the household electric appliances, depending on the control signals or price signals transmitted by energy companies.

4. Currently Utilized Power System Protection

Currently, in case of emergency, the power system can use different energy rationing. It is necessary to protect power system against overload and break-up:

- When there occurs large faults that manifest themselves with large power deficit, it is necessary to automatically counteract by reducing the power consumption in EPS. An ALS (automatic load shedding) is doing exactly that. Under-frequency relays which load-off certain consumer groups are ALS actuators. ALS automation prevents the frequency avalanche in the system. The protective relays are used for automatic and gradual under-frequency load shedding;
- Deliberately taken preventive measures e.g., load rotation or rolling blackout, which are implemented without the knowledge and consent of the end customers. Rolling blackouts are used even today in developing countries or even in developed countries. For example, they have been used in Japan after the earthquake and tsunami in 2011, due to power deficit in their EPS;
- The introduction of power levels and administrative calling customers from relevant groups to introduce power consumption reduction. The fact that, a reduction had been done can be seen in the measured data. Therefore, this is the administrative action and due to reasons beyond the control of the energy company, customer is not entitled to any bonus for this action and for an obligation to reduce power consumption. Levels of power restriction were introduced, e.g., in Poland in August, 2015;
- The DSR, where is it assumed that, actions are carried out with the consent of the customers and with the approval of their specific activities. The recipients receive some gratification, usually financial. In this case, the DSR uses such solutions, which are not intended to deprive the specific audiences total

electricity supply, only temporarily restricts their power demand, e.g., lowering the threshold of maximum power in smart energy meters, use of very high energy prices CPP, etc. An applicable solution is also a complete customer switch off of energy delivery, but consumers receive appropriate gratification for the use of such DSR programs. There can be mentioned: interruptible/curtailable rates and direct load control, tariffs, reasonable discount for incidental shutdown. The aim is to ensure that, such activities were experienced as minimal as possible by the end customers. In order to relieve the power system, customers have to make a reduction in their power demand.

Activities undertaken to reduce the demand for power are preventive measures. If a power system overload is taking place and the frequency falls, then the ALS automation takes action.

This solution has the advantage that, the decision of the load shedding based on measuring the grid frequency is taken in distributed devices, without sending any control signals. The final result can not be predicted by the central frequency regulator because it can not control such action of home appliances.

This solution is a development of the concept described by the author in two other publications [6, 7], see also Ref. [5, 8].

5. Smart Energy Meter Will Control Home Devices Based on the Measured Grid Frequency

A smart meter will be measuring the frequency of the power grid. The meter will control home devices based on the measured grid frequency (Fig. 1).

In case when the measured value falls below the specified frequency threshold, the smart meter will turn off some home appliances. There is also a possible variant where the smart meter measures the frequency and sends a signal to the HAN controller, which controls home appliances [6].

The new approach to power grid security against overload is by automatic control of the household appliances in the HAN through smart energy meter or HAN controller based on measurements of grid frequency. If the mains frequency falls enough to exceed the under-frequency threshold defined in the smart meter, the meter will send control signals to some devices and disable them or force them to restrict significantly the power consumption. This way the power system would be protected from the effects of overload (Fig. 2).

If the household uses HAN, in the event of sending control signals limiting demand for power and signals based on frequency drop they would have the priority in relation to price signals. First of all, energy demanding devices would be controlled.

After switching off multiple devices, the grid frequency reaches the rated value. In such situation, there is a risk of re-activation of the appliances, if only the frequency again reaches the nominal value. Such action on multiple devices would be very detrimental to the devices themselves, as well as for control of the frequency in the electrical power system. Therefore, there has to be applied a time delay from fixing the frequency at nominal value to reclosing of the devices.

Advantages of this solution are as follows:

(1) for the customer

- One smart meter could control work of many household appliances;
- Control of household appliances by the energy meters would not increase the purchase price of household appliances, in opposite as if the under-frequency sensors would be installed in each home appliance;
- A client itself could make the choice in the HAN network which of the loads would be turned off in case of system overload, in the lack of load reduction, e.g., to the required power level, the meter would automatically completely turn off the power at the end customer location;
- Operation of this type of security is almost

imperceptible to the owner of electrical appliances, while disabling of the entire line at the substation will automatically shut off the power for large groups of consumers;

(2) for the national power dispatch

• Theoretically, it would allow the national power dispatch to lower the spinning reserve. This would reduce the unnecessary power generation. With this solution, fuel would be spared and this would have an impact on the environment by contributing to reduction of greenhouse gases emission;

• Under-frequency threshold of relay would be higher than the threshold in the substation that is why the energy meter would be more sensitive to frequency drops than the substation automation. That is why, at least theoretically, it would prevent a failure of the line, because the first detection and reaction to frequency drop would occur even before action is taken at the station. There will be the under-frequency relays installed;

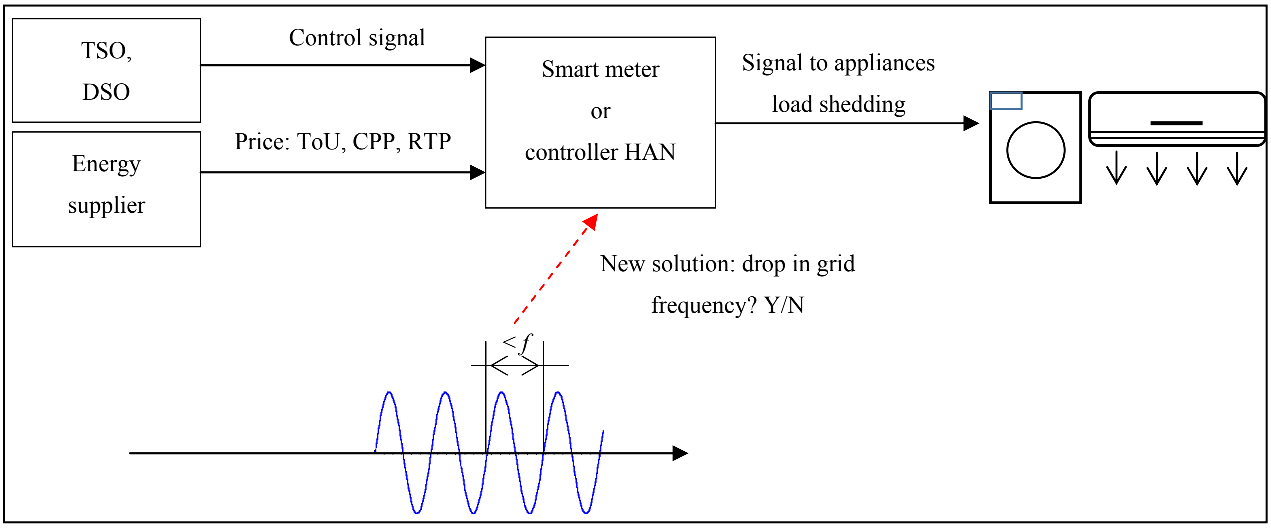

Fig. 1 Smart energy meter controls home devices based on the measured grid frequency.

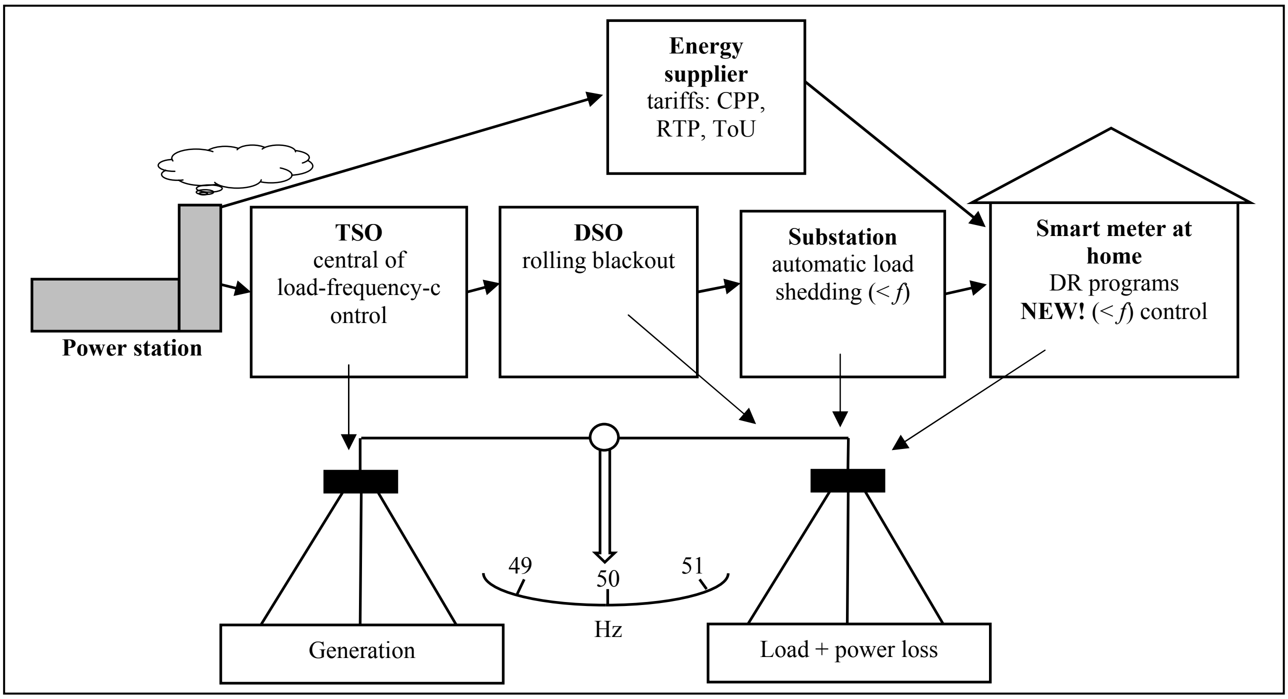

Fig. 2 Tools of utilities of load and frequency control.

- Under-frequency relay activation time is the moment of the overload of the power system, when the expensive time zone takes place in the multi-zone ToU tariffs or critical prices in CPP. Of course, the relationship that if energy prices are high, the frequency drops not always occurs simultaneously. High prices on the wholesale energy market occur when there is a peak load in the power system. In order to cover this demand, there is a need to run expensive, no green power peak generators, which often work irregularly, only a few hours a day, while many costs of their operation are fixed (e.g., the cost of maintenance and staff). They can cover the current demand for energy in the network and then there is no frequency drop, but high energy prices apply on the wholesale market;
- The proposed solution can facilitate the stabilization of labor in the autonomous power supply system or microgrids, which are working in an isolated mode of the grid and they are powered by spinning generators with regulation of frequency;

(3) unnecessary ICT network

- Each smart meter, which controls devices in case of frequency drop, would operate completely independently. This meter does not need a large AMI (advanced metering infrastructure) to know when to control household appliances. It does not need a central system of supervision and control, or receiving or sending signals using communication technologies;
- A smart energy meter, which should detect frequency drop, would be installed by DSO (distribution system operator). In the event of its malfunction, the operator could easily replace it with another one;
- Grid operator could, in specific cases, enable or disable functions of control devices via a smart meter, based on the detected frequency drop;
- The DSO would receive limited amount of data processed and transmitted in AMI. It would also save energy. It allows relieving of the power system in situations of communication problems on the line server-concentrator-smart meter;
- Control of devices, via a smart meter based on proven frequency drop of the power system would allow to relief the system in pre-emergency states, also in case of failure of the wide area network, communication technology used or the surveillance system of the DSO, etc. Thanks to this, the proper functioning of the whole critical infrastructure (power grid) would not be dependent on the proper functioning of other non-critical infrastructure (e.g., telecommunication networks, wide area network);
- Such a solution would be completely protected against interference by cybercriminals—it is easier to modify control signal than the frequency of power grid;
- Response effectiveness of security which is based on consumption data from smart meters in individual households or entire subnet referenced to measure of the frequency would be easily verifiable;
- An energy meter at any time would be able to determine the current power consumption of the household. In this case, it would also have information on whether there is actual ample opportunity to make a reduction in demand for power; in the case of sending control signals, energy meter will also have feedback about whether the actual required reduction in demand occurred.

Disadvantages of the solution are follows:

- In the event of a mass use of smart meters, which would control household appliances based on the detected declines in frequency and mutually uncoordinated work of such meters could result in too big disburden to the system, because the smart meters may shut off too many devices;
- There is a possibility of too much relief to the EPS, in this case, the frequency increase could occur and the appliances start again, causing overloading the power system. Such action would result in frequency fluctuations and would be detrimental to the consumers. Therefore, there is a need for even a slight variation in under-frequency threshold in different

devices. In addition, it is necessary to differentiate the delay in reclosing devices in situations where mains frequency reaches the nominal value;

- Lack of coordination between the different devices performing the load reduction;
- Must utilize well-coordinated operation (tripping thresholds) of such devices with variable frequency control in the EPS. There is a risk of tripping in the event of normal operation of the power system. Currently, if there is a decrease in frequency (activation of the primary control) then the information about this fact is being pushed to the central frequency controller and specific measures are taken to increase the level of generated power (secondary control). In such case, if the device would no longer work, the frequency would slowly reach the nominal value, however, the load would be deprived of electricity power, but in the power system, there would exist some unused power capacities;
- Some customers may not accept such mode of operation of its appliances, assuming they paid for the devices, so the appliances have to work when clients expects and needs them; in this case, it is the issue of adequate customers motivation, willing to commit a possibility of using such functionality;
- Controlled by smart meters based on frequency measurements do not differentiate between customers. Therefore, the order of load reduction at certain customers may be purely coincidental. It also shows the necessity of differentiating thresholds;
- The grid frequency is a global parameter, in the steady state of the EPS, the frequency has the same value anywhere, as a matter of some discussion is the problem of frequency drop in the case of synchronous connection for many national electricity systems, each of which is reinforced by other systems, a noticeable frequency drop occurs only once if the power systems continental level will be significantly overloaded;
- In the case, if there are DC EPS or the AC EPS in which frequency control is carried out in a different way than by the rotating generators e.g., with power electronics, there has to exist detection of an overload of the power system in another way, than on the basis of frequency. Power electronic systems overload does not reduce the grid frequency.

6. Conclusions

The described ability to control devices (utilizing the load shedding) via smart energy meters in the event of the frequency drop of the nominal value allows stabilization of the power grid operation.

The proposed solution changes the current thinking about balancing the EPC and controlling the grid frequency. It seems that, there exists a relatively cheap solution, bringing a lot of benefits. With the introduction of these solutions on a massive scale, it would be necessary to change the methods of adjusting the frequency in the power system.

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