USE OF DEMAND SIDE RESPONSE SYSTEM FREQUENCY CONTROL IN EMERGENCY AND RESTORATION

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ABSTRACT

This paper deals with one of the main topics introduced in the upcoming Network Code on Demand Connection (or Demand Connection Code, DCC) - Demand Side Response (DSR). This paper is focused on DSR SFC, which according to current wording of the Code will be mandatory for Temperature Controlled Devices (i.e. freezers, electric heating). Temperature Controlled Devices are expected to help restore system frequency to its nominal value by adjusting their temperature set point. This paper deals with new dynamic model of Temperature Controlled Devices and the influence of DSR SFC in island operation.

INTRODUCTION

One form of Demand Side Response (DSR) specified in the Network Code on Demand Connection [1] is System Frequency Control (SFC), the decreasing or increasing set temperature proportionately to frequency deviation. Temperature Controlled Devices are for example: fridges, freezers, heat pumps, water heaters, air conditioning and electric heating.
This paper presents a new dynamic model of frequency-controlled thermostatic load, more specifically water heater and electric heating. This model was implemented into network simulator MODES. Simulations of power system dynamic behavior in an island operation were performed.

THE MATHEMATICAL MODEL OF FREQUENCY-DEPENDENT TEMPERATURE CONTROLLED DEVICES

An Irish study presented in [3] shows that the DSR SFC shall have influence on the target temperature proportionate to frequency deviation with a dead band around the nominal system frequency 50 Hz according to Fig. 1.
Fig. 1At first let us examine behaviour of the electric water heater for variable water temperature set point T_R. Heating water with temperature T_W can be represented (when neglecting losses and water consumption) by a simplified equation:

$$mc\frac{dT_W}{dt} = P*S(T_R\text{-}T_W)\ ; \quad S=1 \text{ if } T_R\text{-}T_W>0, \quad S=0 \text{ if } T_R\text{-}T_W<0 \qquad (1)$$

Where:

- c … Water thermal capacity (kJ*K^{-1}*kg^{-1})
- m … Water mass (kg)
- P … Power of heating coil (W)
- S ... ON/OFF function (1-ON, 0-OFF)

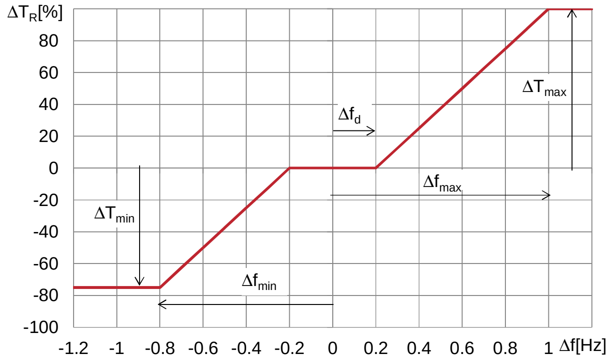

Fig. 1 Parameters of DSR SFC provided by Temperature Controlled Devices

From this equation it is clear that the water temperature set point does not adjust proportionately to frequency deviation as shown in Fig. 1. If the frequency deviation Δf higher than the Δf_d, power is increased in steps (if frequency decreases is does not respond because it is not possible to change accumulated heat back to electric power). Power increase is time-limited, until the water heats up to a newly set temperature value $T_R=T_{R0}+\Delta T_R$. The increased load (power consumed by heating coils) duration depends on the frequency deviation magnitude Δf. To obtain the approximate dependency of aggregate consumption of boilers on frequency deviation it would be necessary to specify a different insensitivity magnitude Δf_d for groups of boilers in an area.
Now we look at electric heating. We can write a simplified equation of changing temperature in the room T_{IN} (considering only conduction losses). Outdoor temperature is constant.

$$K_S\frac{dT_{IN}}{dt} = P_S*S(T_R\text{-}T_{IN})\text{-}K(T_{IN}\text{-}T_{OUT}) \qquad (2)$$

Where:

- K_S … Building thermal inertia constant
- P_S … Power of a single heating coil
- S … Number of heating coils in use
- K … Heat transmission losses coefficient
- T_{out} … Outdoor temperature

Fig. 2 shows the *S*-function depending on difference T_{in} - T_{out} for three-heat-coils heater – red line.

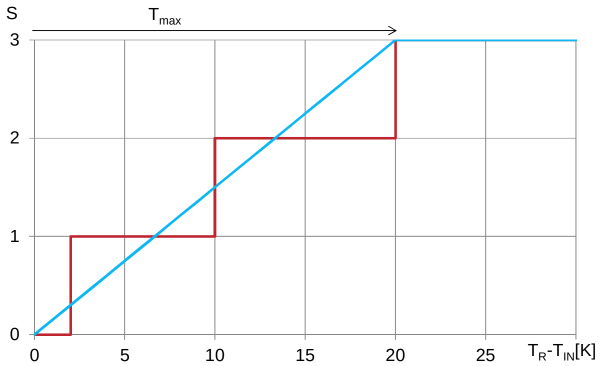

Fig. 2 Number of switched on heat coils depending on temperature difference

To simplify the analysis we consider a linear approximation of the *S*-function - blue line. Then we can rewrite equation (2) to:

$$K_S\frac{d\Delta T_{IN}}{dt}=\frac{P}{T_{MAX}}(\Delta T_R\text{-}\Delta T_{IN})\text{-}K\Delta T_{IN} \quad \text{if } T_R\text{-}T_{IN}>0$$
$$K_S\frac{d\Delta T_{IN}}{dt}=\text{-}K(T_{IN}\text{-}T_{OUT}) \quad \text{if } T_R\text{-}T_{IN}<0 \qquad (3)$$

Where:

P …Total power of heating coils

T_{MAX} …Maximal temperature difference from Fig. 2

The first equation applies to heating; increasing load if frequency deviation is positive. The second equation describes cooling; decreasing load if the frequency deviation is negative.

These equations can be modified to a more suitable form:

$$T_H\frac{d\Delta T_{IN}}{dt}+\Delta T_{IN}=\zeta^*\Delta T_R \quad \text{if } T_R\text{-}T_{IN}>0$$
$$\zeta=\frac{P}{(P+KT_{MAX})} \qquad T_H=\frac{K}{\frac{P}{T_{MAX}}+K} \qquad (4)$$
$$T_C\frac{d\Delta T_{IN}}{dt}+\Delta T_{IN}=T_{OUT}\text{-}T_{IN0} \quad \text{if } T_R\text{-}T_{IN}<0; \quad T_C=\frac{K_S}{K}$$

Where:

T_{IN0} … Initial room temperature

If the heating power P covers the building losses at a temperature difference 40 K and $T_{max}=20\ K$, ξ is equal to *2/3*. T_H and T_c are relevant time constants for heating and cooling. Tc is three times longer than T_H.

Now to calculate the time behaviour of temperature change ΔT_{IN} after step change ΔT_N. Fig. 3 shows ΔT_{IN} calculated from (4) with $\Delta T_R=+/\text{-}10\ K$ respectively.

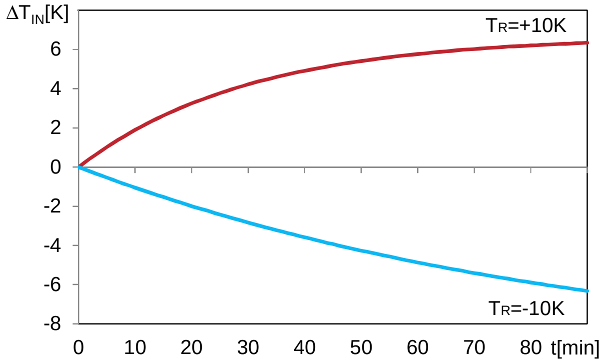

Fig. 3 Indoor temperature change

For a positive change $\Delta T_R=+10\ K$ the indoor temperature increases exponentially with time constant T_H up to 2/3 of the required temperature change. For a negative change $\Delta T_R=\text{-}10\ K$ the indoor temperature decreases exponentially with time constant T_C down to outdoor temperature (when $T_R < T_{OUT}$). With known temperature time behaviour we can estimate the power changes illustrated in Fig. 4.

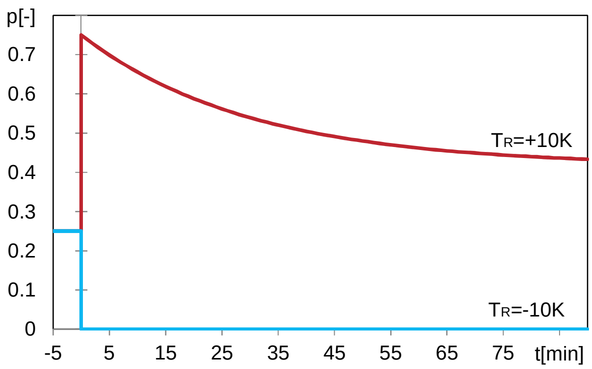

Fig. 4 The heater power relative change after $\Delta T_R=\pm 10$ K change

After a positive change of desired temperature ($\Delta T_R > 0$) the power increases sharply. As the building heats, the power exponentially decreases to a new steady value (higher than before because the thermal losses are higher than in initial state). Increased power during transient state was converted into heat accumulated in the heated space (e.g. building). If a negative change of ΔT_R occurs, the power is instantly reduced to zero.

To implement a model of frequency-dependent load into the network simulator MODES a characteristic shown in Fig. 5 is used.

For frequency decrease ($\Delta f < 0$) different settings of dead band for individual thermostatic loads are expected. In aggregate the dependence of load on frequency would be approximately linear with gradient k_-

Change of power consumption ΔP due to frequency deviation Δf is represented by equations (5).

$$\Delta P = P_0(X+Y); \quad T_H\frac{dY}{dt} + Y = -\zeta * X; \quad X = k_+(\Delta f - df_D) \quad \text{if} \quad df_D < \Delta f < df_{MAX} \tag{5}$$

$$\Delta P = P_0 X; \quad X = k_-(\Delta f + df_D) \quad X > -1 \quad \text{if} \quad \Delta f < -df_D$$

ΔP has two parts: static part X and dynamic part Y.

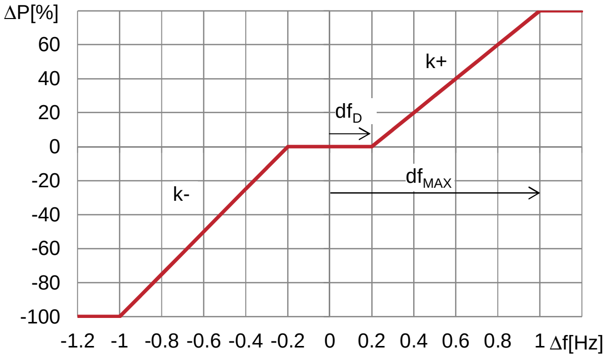

Fig. 5 Simulation model of frequency-dependent load

BEHAVIOUR OF FREQUENCY-DEPENDENT THERMOSTATIC LOAD IN ISLAND OPERATION

Network model allows us to analyse the behaviour of load during frequency changes. These changes are very small in normal operation; therefore it is convenient to study an island operation (when the part of network is separated from the bulk transmission system).

For testing of the DSR SFC in island operation a generic model was used. This simplified model represents basic features of a distribution network supplied by a 400/110 kV transformer from the transmission system. Its single-line diagram is shown in Fig. 6.

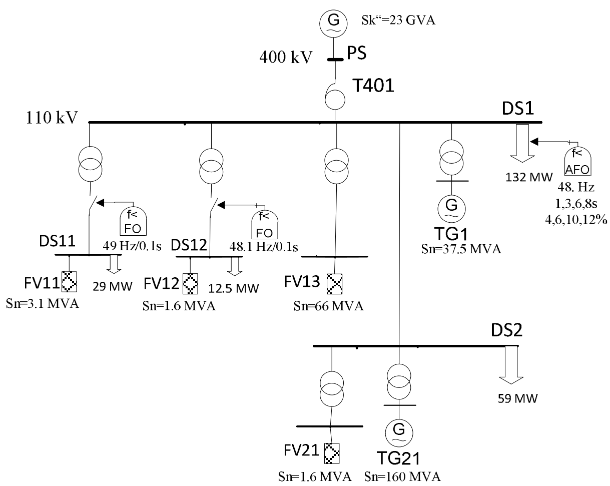

Fig. 6 Single-line diagram of a generic model representing a distribution system

The 110 kV region is modelled in a simplified way by two nodes: DS1 and DS2. Distribution transformers 110/22 kV with consumption and photovoltaic power plant, aggregated generation of conventional power plants TG1 and photovoltaic power plant FV13 and aggregated consumption (connected to the 22 kV side) are connected into the node DS1. Particular feeders can be equipped with frequency protections with different setting for under frequency load shedding (UFLS). An aggregate consumption, photovoltaic power plant FV21 and a conventional generator TG21 are connected into the node DS2.
Transition to island operation was initialized by outage of the transformer T401. Generation output power changes were induced by moving clouds across the photovoltaic power plant FV13 (PV model is described in [4]).
Two cases were studied. In the first case there was no frequency-dependent thermostatic load. This means that on only the regular load frequency response of approx. 1 %/Hz (load decreases by 1 % if frequency decreases by 1 Hz) is considered. In the second case a quarter of consumption connected to node DS2 was modelled as frequency dependent. The equations (5) were used for this part of the load with parameters from Tab. 1.

Tab. 1 Parameters of frequency dependent thermostatic load

	k_+ (-)	k_- (-)	T_H (min)	ζ (-)	df_D (-)	df_{MAX} (-)
TERMDF	50	62.5	20	0.66	0.004	0.02

Fig. 7 shows waveforms of the frequency deviation Δf and load P in the node DS2. The first case is depicted by a thin line and the second case by a bold line.

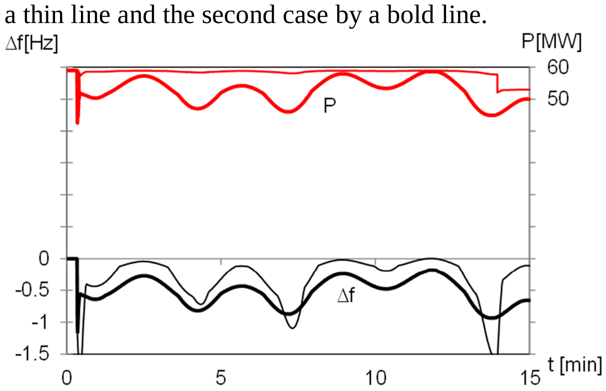

Fig. 7 Frequency deviation Δf after transitions to island operation.

After transition to a deficient island operation the frequency decreased and when it reached the threshold 49.0 Hz the node DS11 was disconnected by a frequency protection relay.
In the first case (without frequency-dependent thermostatic load) frequency fell below 48.1 Hz which caused disconnection of the node DS12 by frequency protection relay. At the end of the simulation a local

UFLS shed load in the node DS1 due to frequency decrease below 48.0 Hz.
If the frequency-dependent thermostatic load was active (case two) the frequency remained higher than 49.0 Hz despite the changing infeed from photovoltaic power plants due to changing consumption in node DS2. This power response prevented load shedding in nodes DS12 and DS1.

CONCLUSIONS

The introduction Demand Side Response System Frequency Control by the Network Code on Demand Connection can help stabilize frequency in an island operation. The main condition is sufficient speed of the load response to the frequency deviations.

REFERENCES

[1] Draft Network Code on Demand Connection, version of 21st December 2012. Available at: http://networkcodes.entsoe.eu/wp-content/uploads/2013/08/121221_final_Network_Code_on_Demand_Connection.pdf

[2] K. Máslo: The general purpose network simulator MODES, in proc. 4th international workshop on EPSCC 1997, Rethymno, Greece

[3] ENTSO-E Demand Connection Code – Frequently asked questions, Available at: https://www.entsoe.eu/fileadmin/user_upload/_library/resources/DCC/ENTSO-E_finalises_DCC/121221-DCC_-_Frequently_Asked_Questions.pdf

[4] M Pistora., K. Máslo: Impact of embedded renewables on transmission and distribution network, 10th International Scientific Conference Control of Power Systems, May 2012 Tatranské Matliare