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Modeling and Simulation of Multi-Vector Energy Systems

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Abstract-- **The energetic scenario shows ever growing energy consumptions and the need of an optimal management of different types of energy distributed resources. The synergy among different energy carriers could be exploited to achieve a more efficient use of the resources, an increase of the reliability of the electrical system, a greater integration of renewable generation in the system and both a demand and supply side management. In this paper a simulation environment of multi-vector energy networks is presented. In particular, the paper focuses on the role that CHP units may have in coupling electric and thermal networks and their feasibility of participating to the distribution network voltage regulation.**

Index Terms-- **multi-vector network, distributed generation, optimization, energy hub.**

I. Introduction

The ever increasing growth of energy consumptions, which concerns not only electrical demand, sets against the needs to respect economical, political and environmental constraints due to different goals, as well as the reduction of harmful emissions, the need to differentiate the combustible park, economical use of resources, demand supply etc.

Distributed resources have demonstrated the potentiality to achieve these goals. The availability of new technologies (i.e. microturbines, fuel cells and hydrogen based solutions) combined with traditional ones (like internal combustion engines) make small-scale environmentally compatible generators more suitable than traditional vertical structures for energy production and distribution to end users.

Different types of Distributed Generation (DG) will characterize the electric system in the next future. Small-scale generators, except off-shore wind farms, and renewable generators influence the operation and management of the network and different models of generation and supply approaches have to be developed. In particular DGs are not optimally located and many types of DGs could be partially unpredictable and not dispatchable.

Considering the great diffusion of co-generation and tri-generation plants that exploit the synergy between different energy carriers, future networks will be characterized by the optimal integration of different energy carriers [1].

In this way, mutual conversion (and possibly storage) of the different energy forms within the framework of a distributed system are required to achieve hybrid systems. A multi-source multi-product energy system is based on synergy among electrical, thermal, chemical and other energy carriers, which adds degrees of freedom to both demand and supply side management demand and to the reliability of the whole system.

In this framework, only a new energy market system has the capacity to prompt for an optimal management of these degrees of freedom. Free energy markets will drive the consumers-producers management of their own installations in a multi-vector network where each node is important for the management.

In order to suitably represent the interactions among different energy vectors, the energy hub concept has been adopted [2], [3]. An energy hub is a generalized system for generation, conversion and storage of different forms of energy and may thus be efficiently exploited for optimising the operation of multi-vector energy networks.

In this paper a multi-vector energy system simulation environment is presented. Optimal power flow techniques are applied to solve the problem; in particular the optimisation tool is focused on investigating the possibility to obtain a virtuous behavior of distributed resources enabling their participation to network voltage regulation.

II. Energy Markets in a multi-vector network

All different energy carriers don't exist alone but they are considered and managed independently, except for co-generation and tri-generation plants that have already demonstrated to be the most efficient form of combined generation. In this perspective a multi-vector network is a natural consequence to achieve energy efficiency needs, to ensure sustainability and a more rational use of the energy. A hybrid system facilitates the management of such energy resources which need of energy carriers conversion, as well as storage facilities.

The interactions among different energy networks take places at the nodes. A node could be a real physical node or a virtual node, where different devices are aggregated and can exchange/generate/convert different forms of energy, suitably represented by energy hubs. The various networks are thus coupled by the energy hubs, as pictorially shown in Fig. 1.

Consequently each node takes a greater importance in the system in the Demand-Side Management (DSM) and the possibility of a real-time observability, controllability and process efficiency optimization becomes a key need.

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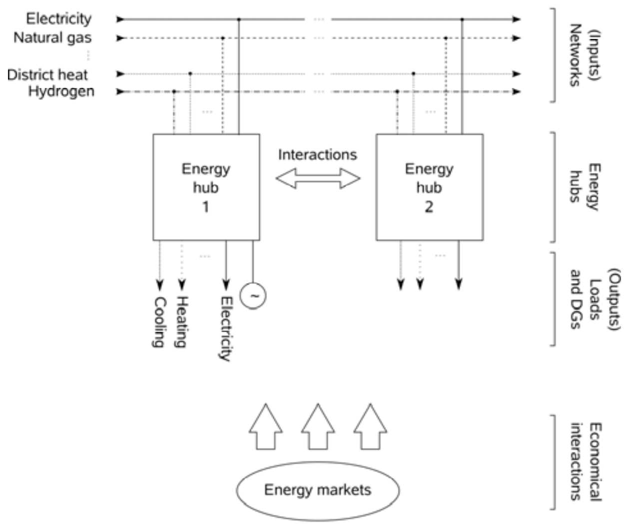

Fig. 1: Example of multi-vector network with energy hubs.

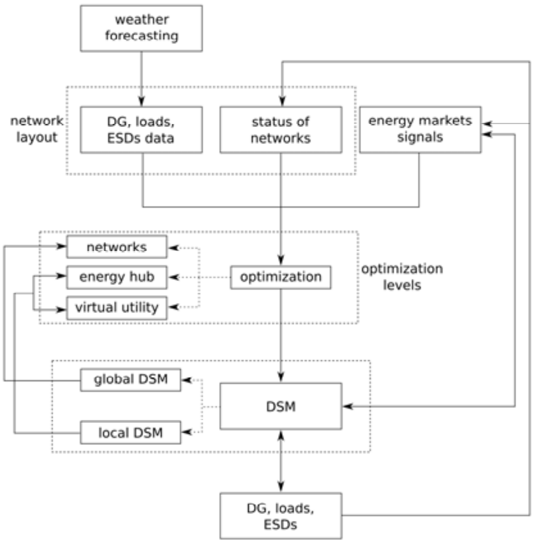

Fig. 2: Conceptual scheme of multi-vector algorithm.

Economical tariffs are the most effective lever to incentivize producers to actively participate in the network management.

In this perspective, the best network configuration could be obtained as the optimal economical solution. The best network configuration means better energy services, fewer environmental costs, improvement in the utilization of resources, suitable voltage profiles etc.

Considering the strong impact of energy prices in present energy policies, energy markets system will be improved in the next future. In particular, innovative price list system and a plurality of energy markets are necessary to provide suitable signals to each active element of the network as in an internet-like model. Furthermore, it seems interesting to translate technical constraints or network needs in suitable price signals which have to reach each bus. In this way, an optimal behavior should be naturally obtained considering the highest owners' revenue. Owners could also have distributed generators and a multi-area problem have to be considered, thus applying the Virtual Power Plant (VPP) concept, i.e. a cluster of distributed generation/load installations which are driven by a common central control system.

III. Simulation Environment

A comprehensive software platform for simulating and optimizing the operation of multi-energy vectors network is under development [4]. A conceptual scheme of the algorithm is shown in Fig. 2. The algorithm may be applied indifferently to single (e.g. electrical) or multi-energy vector networks.

The core of the system is represented by the models of the network, energy hub and virtual utilities.

The optimization is always performed on the whole system but may have different concurrent optimization functions depending upon the specific goals (local optimization of energy hubs, virtual power plant or entire integrated network operation). In this way technical constraints (such as voltage limits, line loadings, etc.) are always catered for.

As shown in Fig. 2, the software platform should provide a complex system of signal interaction between a post-processing of optimal results and energy market and networks system. Signals are worked out by a DSM and sent as economical hint to energy markets system or as technical issues to single physical entities (DGs, loads, energy storage devices) and to networks, energy hubs and virtual utilities.

Optimization is based on energy tariffs and energy markets signals which can be suitably modulated on the basis of network needs in order to provide incentives to the producer/consumer to operate near the network optimum (for example minimum losses, no congestions, acceptable voltage profiles).

The availability of smart multi-metering at customer premises as well as new intelligent ICTs (Information and Communication Technologies) for networking and data management are required.

So far the optimisation tool representing the core of the system has been implemented, while energy markets and DSM models are under development. This tool, however, is a self-consistent program which may be applied for specific analysis such as investigating the role of storage devices [5] or the application study reported in this paper.

IV. Modeling

A. Energy hub

Energy hubs are interfaces between different energy vectors, special nodes where generation, conversion and storage could take place. Their representation may be completely defined by the following generic matrix equation:

$$\underbrace{\begin{bmatrix} L_\alpha \\ \vdots \\ L_\omega \end{bmatrix}}_{\mathbf{L}} = \underbrace{\begin{bmatrix} c_{\alpha\beta} & \cdots & c_{a\omega} \\ \vdots & \ddots & \vdots \\ c_{\omega\alpha} & \cdots & c_{\omega\omega} \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} P_\alpha \\ \vdots \\ P_\omega \end{bmatrix}}_{\mathbf{P}} - \underbrace{\begin{bmatrix} s_{\alpha\beta} & \cdots & s_{a\omega} \\ \vdots & \ddots & \vdots \\ s_{\omega\alpha} & \cdots & s_{\omega\omega} \end{bmatrix}}_{\mathbf{S}} \underbrace{\begin{bmatrix} \dot{E}_\alpha \\ \vdots \\ \dot{E}_\omega \end{bmatrix}}_{\dot{\mathbf{E}}} \quad (1)$$

where $\boldsymbol{L}$ and $\boldsymbol{P}$ are output and input vector respectively and $\boldsymbol{C}$ is the coupling matrix between different energy vectors (indicated by Greek letters). The coefficients of the coupling matrix describe the conversion relationships between different energy vectors. The model may account for storage devices by means of a so-called storage coupling matrix, $\boldsymbol{S}$, whose coefficients consider both conversion and charge/discharge efficiencies, which multiplies the energy derivates vector $\dot{\mathbf{E}}$. More details are available in [2], [3].

In this work hub units have no storage devices and their model is defined by the following generic equation:

$$\begin{bmatrix} L_{el} \\ L_{th} \end{bmatrix} = \begin{bmatrix} \eta_t & 0 & \upsilon\eta_{CHP,el}(\cos\varphi + i\sin\varphi) \\ 0 & \eta_{ex} & \upsilon\eta_{CHP,th} + (1-\upsilon)\eta_f \end{bmatrix} \begin{bmatrix} P_{el} \\ P_{th} \\ P_{gas} \end{bmatrix} \quad (2)$$

where η_t, η_{ex}, $\eta_{CHP,el}$, $\eta_{CHP,th}$, and η_f are respectively transformer, thermal exchanger, electrical CHP, thermal CHP and furnace efficiencies; L_{el} and L_{th} are electrical and thermal loads; P_{el}, P_{th} and P_{gas} are electrical, thermal and natural gas input power and υ represents the natural gas dispatch factor between CHP and furnace (if present).

To be noted that L_{th}, P_{th} and P_{gas} are real variables whereas L_{el} and P_{el} are complex variables enabling to cater for both active and reactive electrical power ($\cos\varphi$ is the CHP power factor).

Control of the reactive power component is fundamental in order to enable the energy hub to participate to the electrical network voltage regulation.

B. Networks

Electrical and thermal network models can be represented by nodal power balances:

$$P_m - \sum_{n \in N_m} P_{mn} = 0, \quad (3)$$

which means that the sum of all branch flows to bus *m* is equal to its nodal power injection. To be noted that for the electrical network P_{mn} are complex power variables whereas for a generic pipeline network (gas, water or hydrogen) these are real quantities.

The pipeline flow is defined as

$$f_{kj} = M_{kj} S_{kj} \sqrt[m]{S_{kj} \Delta p_{kj}} \quad (4)$$

where f_{kj} is the line flow [m^3/h], M_{kj} is proportional to the rate between a given power of the diameter (D, [m]) and length (L, [m]) of the pipeline Δp_{kj} [Pa] is the pressure gap between busses *k* and *j*, S_{kj} indicates the direction of the flow ($S_{kj}=sign(\Delta p_{kj})$), and *m* depends on the network pressure level.

This equation is valid for both gaseous and liquid fluids (Δp_{kj} and M_{kj} change according to the hypothesis). In this specific case, the Darcy's equation has been implemented for the district heating network using water as thermal vector (120° C forward and 60° C return). To the sake of simplicity, only hydraulic calculation has been done, disregarding temperature and temperature dependent behavior.

The nodal balance should also consider possible pump or other pressure control elements as valves, but no such elements have been considered in this work.

More detailed models can be found in [6], [7], [8].

V. OPTIMISATION

The problem of optimization is characterized by an objective function to minimize (or maximize) and a set of unknown quantities or variables (x) that affects the objective function.

The optimal value of the problem is a scalar real value. The objective function could concern technical or economical purpose as losses, voltage variation, emissions, generation and operational costs. Multiple objective functions are often considered to simultaneously optimize a number of different objectives. In this case, suitable coefficients are used both to make homogenous different objectives and to assign more or less importance to each one (weight coefficients).

The optimization could consider a single instant or a multi-period. In particular, the multi-period optimization is required when storage devices are present. In such case, it is important to known what happens before and after a present instant to optimal manage a storage device which has the key role to free power generation/consumption from instant balance.

In this paper, the considered objective function is an economical one, where the sum of import/export power costs for each energy hub has been taken into account:

$$\min f(x) = \sum_{h \in H} c_{gas} P_{h,gas} + c_{th} P_{h,th} + c_{el,active} P_{h,el} + c_{el,reacive} Q_{h,el} \quad (5)$$

with c_{gas} natural gas energy cost, c_{th} thermal energy costs, $c_{\mathrm{el,active}}$ active electrical energy cost and $c_{el,reactive}$ electrical reactive energy cost.

The optimization problem is a single step optimization considering absence of storages. The thermal import/export flow of the unknown-injection bus has been taken into account in the objective function with a component cost as an import/export energy hub thermal power.

The objective function is to minimize the overall operational cost of energy hubs, which may thus be considered as a sort of virtual utility.

Practical systems are very often formulated with some constraints imposed on their variables. Optimisation of such problems must be carried out within the limits of these constraints. In this way, a vector $\boldsymbol{x}$ that satisfies the constraints is an admissible solution of the problem:

$$x = \begin{bmatrix} \vartheta & \mathbf{V} & \mathbf{P} & \mathbf{Q} & \mathbf{p_{th}} & \mathbf{f_{th}} & \mathbf{P_H^{in}} & \boldsymbol{\upsilon} & \mathbf{cos}\varphi \end{bmatrix} \quad (6)$$

In this specific case the unknown quantities are voltage phase angles (ϑ vector) for each electrical PV and PQ bus, voltage amplitude ($\boldsymbol{V}$ vector) for each electrical PQ bus, active and reactive power ($\boldsymbol{P}$ and $\boldsymbol{Q}$ vectors) for each variable generator and load, pressure ($\boldsymbol{P_{th}}$ vector) for each unknown-pressure bus, flow ($\boldsymbol{f_{th}}$ vector) for each unknown-injection bus, input powers ($\boldsymbol{P_H^{in}}$ vector), dispatch factor ($\boldsymbol{\upsilon}$ vector) and power factor (***cosφ*** vector) for each energy hub.

As listed below, the optimization problem considers a large number of technical constraints, as upper and lower, linear and non-linear constraints. Furthermore, for each energy hub, eq. (2) and (3) represent add-on and necessary system constraints, together with the internal generation limits (for example maximum furnace and CHP input gas power).

$$\left.\begin{aligned}
&\vartheta_{i,\min} \le \vartheta_i \le \vartheta_{i,\max}\\
&V_{i,\min} \le V_i \le V_{i,\max}\\
&P_{i,\min} \le P_i \le P_{i,\max}\\
&Q_{i,\min} \le Q_i \le Q_{i,\max}\\
&I_k \le I_{k,\max}
\end{aligned}\right\} \quad \textit{electrical}$$

$$\left.\begin{aligned}
&p_{th,j,\min} \le p_{th,j} \le p_{th,j,\max}\\
&f_{th,j} \le f_{th,j,\max}
\end{aligned}\right\} \quad \textit{thermal} \qquad (7)$$

$$\left.\begin{aligned}
&P^{in}_{h,\min} \le P^{in}_{h} \le P^{in}_{h,\max}\\
&0 \le \upsilon_h \le 1\\
&0 \le \cos\varphi_h \le 1
\end{aligned}\right\} \quad \textit{energy hub}$$

VI. APPLICATION

A. Case study system

The integrated electrical and thermal case study network is shown in Fig. 3. The electric network is a 20 kV 9-bus radial network, connected to the bulk grid (slack bus N1) through a on-load tap-changer (OLTC) transformer. The 6-bus thermal network represents a portion of a district heating system ("slack" known-pressure bus TH5, pressure 14.5 bar). The two networks are coupled through the four energy hubs H3, H4, H5 and H7.

As shown in Fig. 3, the hubs differ each other by the constituting elements (T = transformer, CHP = combined heat and power generator, E = thermal exchanger) and this is reflected by the values assumed by the coefficients in eq. 3, as listed in table A1 in Appendix. (the size of the CHP units in hubs H3, H4 and H7 is 3.5MWel while in H5 there is no conversion between electrical and thermal energy vectors).

All the electric and thermal network data are reported in Appendix. In the case study all loads are kept constant, whereas two distributed generation settings have been considered, a low generation (I) and a high generation (II) scenario respectively.

In this study the following cost coefficients have been assumed: 3.741 [€/(kWh)] has been adopted as natural gas cost, assuming Italian purchase tariff (0.358 [€/m^3]) [5]. Thermal cost (4.489 [€/(kWh)]) has been supposed 20% higher than natural gas cost to account for efficiencies and other thermal generation costs.

The electrical active energy cost has been considered equal to 8.2 [c€/(kWh)], while the reactive energy cost has been assumed equal to 80% of electrical active energy cost (6.56 [c€/(kVarh)]). Remuneration of reactive energy has been considered in order to incentivize hub generators to produce also reactive power when required as an ancillary service. The above prices apply for both purchase and selling electrical and thermal power, whereas natural gas may only be purchased.

Aim of the optimization is to minimize the hubs operational costs, while respecting all the system constraints and enabling their participation to the electric network voltage regulation.

B. Results and discussion

A selection of the results is reported in Figs. 4 and 5 (electric network voltage profiles) and Table I (energy hubs operational data, power data in pu with P_{base}=1MW). Without any voltage control provision (OLTC transformer set to tap=0 and bus voltage allowed to vary in the range 0.96-1.04 pu) the two distributed generation scenarios lead to the opposite voltage profiles represented by the red dashed lines in figs. 4a and 5a.

Scenario I

In this case of low DG production bus voltages are generally depleted (N8 reaching the minimum allowed limit of 0.96) and the OLTC is considered to intervene by lowering 1 tap thus increasing the network bus voltage levels (blue solid line in Fig. 4a). In the hypothesis of CHPs of the energy hubs instructed to produce active power only (*cosφ*=1), the optimization results in the hubs import/export power conditions shown in column (1.a) of Table I, characterized by a total operational cost of 1178 [€/h].

In order to further improve the network voltage profile, the DSM is supposed to set a minimum bus voltage level equal to 0.98 and the CHPs of the energy hubs are enabled to generate reactive power (*cosφ*<1) within their capability curves. Considering these new constrains, the optimization procedure is run again resulting in the hubs import/export power conditions shown in column (1.b) of Table I and the network voltage profiles of Fig. 4b. It can be noticed that the overall better voltage distribution is achieved with a general increase of the levels of feeder L1 bus voltages. This is attained by the optimized re-distribution of the import/export power of the energy hubs, in particular H4 which is the element connected to the most depleted electric bus (N4).

It is of interest to highlight that the overall operational costs of the 4 hubs participating to the voltage regulation is reduced by 17% with respect to the previous case. Such cost reduction is due to the higher exploitation of the CHPs, enabled by the presence of the thermal network which allows CHPs to modulate their heat production and supply also remote loads (although total gas consumption is increased by 20%, the heat power import through slack bus TH5 is almost zeroed and the CHPs increase their reactive power production of more than 1.2 MVar).

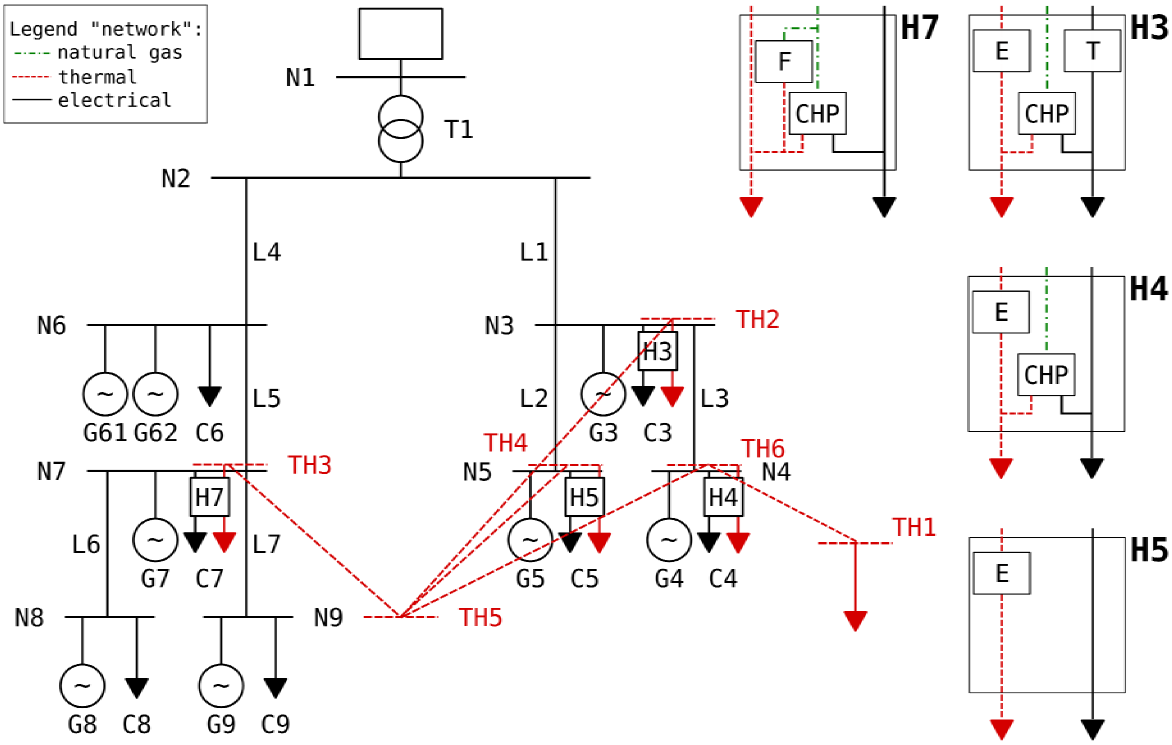

Fig. 3: One line diagram of integrated electrical and thermal system

TABLE. I:
ENERGY HUBS AND NETWORK RESULTS WITHOUT (1.a, 2.a) AND WITH (1.b, 2.b) HUBS PARTICIPATION TO VOLTAGE REGULATION (NEGATIVE SIGN INDICATES EXPORT VALUES)

		Scenario I (tap=-1)		Scenario II (tap=1)	
		(1.a)	(1.b)	(2.a)	(2.b)
H3	P_{el}	0,609	0,983	0,609	0,914
	Q_{el}	0,826	0,818	0,826	0,836
	P_{th}	-1,448	-0,775	-1,447	-0,899
	P_{gas}	2,952	1,905	2,952	2,098
H4	P_{el}	2,151	1,193	2,151	0,910
	Q_{el}	1,012	-0,199	1,012	-0,531
	P_{th}	1,251	-2,320	1,251	-3,439
	P_{gas}	2,264	6,808	2,264	8,233
H5	P_{el}	2,920	2,920	2,920	2,920
	Q_{el}	1,615	1,615	1,615	1,615
	P_{th}	3,337	3,337	3,337	3,337
	P_{gas}	0,000	0,000	0,000	0,000
H7	P_{el}	-0,599	-0,254	-0,599	0,280
	Q_{el}	0,306	0,309	0,307	0,318
	P_{th}	-1,428	-0,433	-1,428	0,253
	P_{gas}	3,953	2,355	3,953	0,830
P_{el}, SL bus		-1.105	-1,385	-13,029	-13,248
Q_{el}, SL bus		7,026	5,700	-0,001	-1,500
P_{th}, SL bus		2,120	0,218	2,120	-0,339
Obj [€/h]		1178,0	979,0	1178,0	927,0

Scenario II

In this case of peak distributed generation, mainly concen-trated on feeder L4, without any regulation action the voltage distribution would be as shown by the red dashed line in Fig. 5a, from which it is noticeable that the two feeders have opposite voltage behavior. In such condition the OLTC would react by increasing 1 tap, thus lowering the network bus voltages and leading to the profile given by the blue solid line in Fig. 5a. As a result, feeder L1 bus voltage levels are considerably lowered with N5 almost reaching the minimum allowed level.

With the CHPs of the energy hubs forced to produce active power only, i.e. no participation to voltage regulation, the optimization procedure leadsd, as it could be expected, to the same hubs import/export power conditions as in the previous scenario (see column (2.a) of Table I).

Similarly as before, the DSM is now supposed to set a minimum bus voltage level equal to 0.98 and the CHPs of the energy hubs are enabled to generate reactive power ($cos\varphi$<1). The optimization procedure is run again resulting in the hubs import/export power conditions shown in column (2.b) of Table I and the network voltage profiles of Fig. 5b.

Once again, the optimized re-distribution of the import/export power of the energy hubs leads to an overall better voltage distribution (in particular the levels of feeder L1 bus voltages) and this is accomplished with almost a 20% reduction of overall operational costs of the 4 hubs.

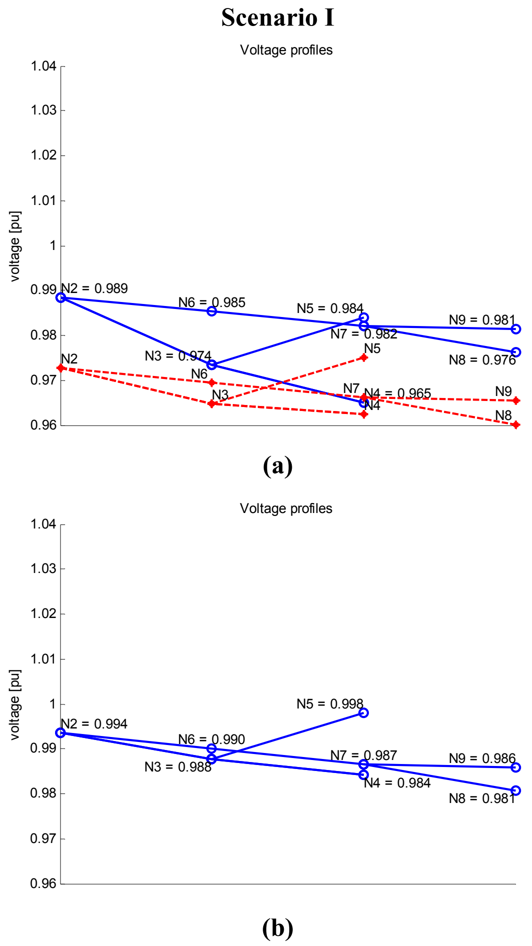

Fig. 4: Voltage profiles - scenario I: (a) OLTC transformer with tap = 0 (red dashed line) and with tap = -1 (blue solid line) without voltage control; (b) OLTC transformer with tap = -1 and voltage control

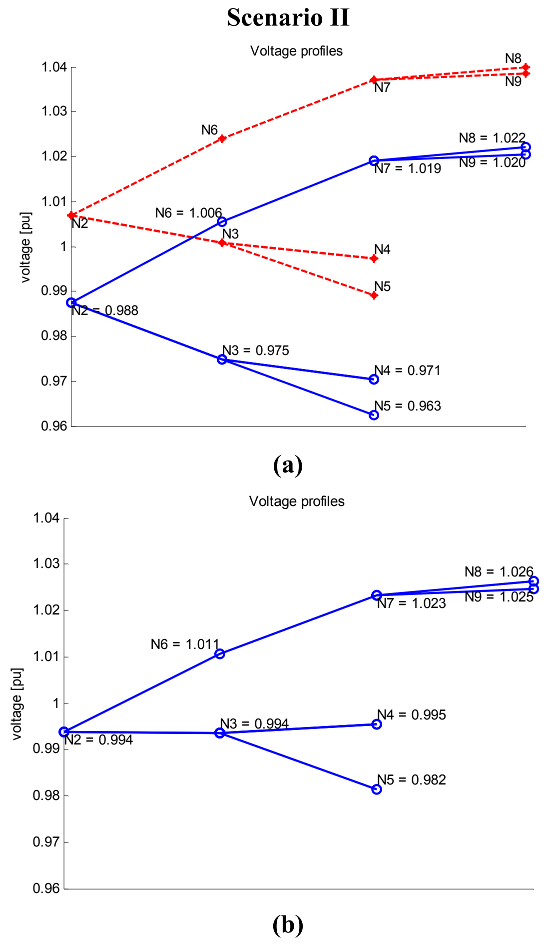

Fig. 5: Voltage profiles - scenario II: (a) OLTC transformer with tap = 0 (red dashed line) and with tap = 1 (blue solid line) without voltage control; (b) OLTC transformer with tap = 1 and voltage control

VII. Conclusions

In this paper an optimal power flow simulation tool for multi-vector energy systems is presented, with specific focus on electrical and thermal networks which are linked by distributed CHP units. This tool represents the core system of a comprehensive simulation environment which is under development and will integrate also models of energy markets, distribution system and demand side management as well as other energy vector networks, such as natural gas and hydrogen.

A case study has been presented in which it is shown that, in an integrated electric and thermal network system, the optimized management of energy hubs provided with CHP units may enable their active participation to network voltage regulation while reducing their overall operational costs.

The optimization is based on cost functions and even better results could be expected by introducing suitably modulated price signals and different tariff scenarios. This aspects will be further investigated in future work.

VIII. Appendix

Data of the energy hubs model, electric and thermal network elements of Fig. 3 are listed below.

TABLE. A.1
Hubs Coupling Matrix Efficiencies

name	η_t	η_{ex}	$\eta_{CHP,el}$	$\eta_{CHP,th}$	η_f
H3	0.98	0.7	0.35	0.45	--
H4	(1)	0.7	0.30	0.55	--
H5	(1)	0.7	--	--	--
H7	(1)	(1)	0.35	0.45	0.9

TABLE. A.2
Electrical Branches

name	l [km]	r [Ω/km]	l [mH/km]	c [nF/km]	I_{max} [A]
L1	5.720	0.268	1.165	10.0	280
L2	6.070	0.352	1.225	8.98	235
L3	4.100	0.320	0.406	290	200
L4	3.740	0.125	0.335	360	400
L5	3.700	0.125	0.335	360	400
L6	5.135	0.206	0.380	340	280
L7	1.575	0.519	1.229	9.00	180

TABLE. A.3
ELECTRICAL LOADS AND GENERATORS [pu, P_{base}=1MW]

	loads		generators			
			Scenario I		Scenario II	
bus	P_{el}	Q_{el}	P_{el}	Q_{el}	P_{el}	Q_{el}
N2	--	--	--	--	--	--
N3	1.630	0.824	--	--	3.50	0
N4	2.830	1.022	--	--	1.25	0
N5	2.920	1.615	3.0	0	2.25	0
N6	4.762	2.384	3.0	0	1.05 7.50	0 2.50
N7	0.570	0.323	--	--	7.50	2.50
N8	2.000	0.987	--	--	2.50	2.50
N9	0.252	0.170	--	--	1.05	0.07

TABLE. A.4:
THERMAL BRANCHES

name	from	to	l [km]	D [m]
L1	TH2	TH5	2.0	0.15
L2	TH3	TH5	1.5	0.15
L3	TH4	TH5	1.0	0.20
L4	TH6	TH4	1.0	0.18
L5	TH6	TH1	0.5	0.15

TABLE. A.5
THERMAL LOADS [pu, P_{base}=1MW]

name	bus	P_{th} [pu]
C1	TH1	0.4081
C2	TH2	0.3150
C3	TH3	0.6270
C4	TH4	2.3358
C6	TH6	2.1205

IX. REFERENCES

[1] G. Andersson, M. Geidl, K. Hemmes, J.L. Zachariah-Wolff, "Towards multi-source multi-product energy systems", ScienceDirect, International Journal of Hydrogen Energy 32 (2007) 1332-1338

[2] G. Andersson, M. Geidl, "A Modeling and Optimization Approach for Multiple Energy Carrier Power Flow", Proceedings of IEEE PowerTech 2005, St. Petersburg, Russia, 2005

[3] G. Andersson, M. Geidl, "Optimal Power Flow of Multiple Energy Carriers", IEEE Transactions on Power Systems, Vol. 22, No. 1, February 2007

[4] L. Carradore, F. Bignucolo, "Distributed Multi-Generation and Application of the Energy Hub Concept in Future Networks", 43rd International Universities Power Engineering Conference, UPEC 2008, Padova, 1-4 Sept. 2008

[5] S. Barsali, D. Poli, S. Scalari, L. Carradore, R. Turri, "Integration of process-side energy storage and active distribution networks and economical optimisation", CIRED 2009, 20th International Conference on Electricity Distribution, Prague , 8-11 June 2009

[6] A.J. Osiadacz, "Simulation and analysis of gas networks", E. & F.N. Spon, ISBN 0-419-12480-2

[7] E. Shashi Menon, "Gas pipeline hydraulics", ed. Taylor & Francis 2005, ISBN 0.8493-2785-7

[8] S. Acha, C. Hernandez-Aramburo, "Integrated modelling of gas and electricity distribution networks with a high penetration of embedded generation", CIRED 2008, Frankfurt, 23-24 June 2008

X. BIOGRAPHIES

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