Intra-Plant Reactive Power–Voltage Control: Practices, Drawbacks and Challenges

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***Abstract*— The paper discusses reactive power -voltage (Q-V) control in a multi-machine steam power plant (SPP). After briefly introducing some of the basic characteristics of synchronous generator's voltage control through automatic voltage regulators, the practices of widely applied manual voltage references setting for Q-V control in SPP is illustrated through several examples of SPP response recorded at site. Further the case studies were developed with the emphasis on the drawbacks of manual intra-plant Q-V control by building a mathematical model of realistic SPP in Matlab-Simulink. Relying on noticed drawbacks the paper highlights the requirements for enhancing SPP reactive power response and voltage support to the power system by coordinated Q-V control at power plant level. Finally, the paper illustrates the achieved performances of coordinated Q-V controller in real SPP.**

***Index Terms*-- Reactive Power Control, Coordinated Voltage Control, Automatic Voltage Regulator**

I. INTRODUCTION

Power quality regulation in power systems requires that voltage magnitudes at all buses in the network are maintained within a certain range under varying loading conditions, ideally from no load to full load. During the normal network operation, voltage and reactive power (Q) control [1], [2] and [3] are typically performed manually by system operator (SO). With the introduction of deregulated electricity markets, power plants have become energy producers that sell the electrical energy at its output (plant's high voltage (HV) bus) to the network. As the MWh is fully recognized as market goods which is acknowledged through is's market price, one decade after deregulation MVAr is still fighting for being adopted as inevitable part of energy price. This pushed the reactive power – voltage (Q-V) control problems aside at all levels of control in power system. However the circumstances are changing nowadays and there is a growing interest in controlling the voltages at power system level due to: i) weak reactive power and voltage supports from synchronous generators (SG) lead to stability problems and black-outs [4]; ii) there is analogy of bulk system control and local LV and MV network control which became of prime importance with large penetration of distributed generators into, by recent time, exclusively passive, highly mashed distribution network.

This paper discusses existing practice in manual Q-V control at the plant level. The direct motivation for introducing the intra-plant Q-V controller was to overcome drawbacks of manual control noticed in practice during large disturbances in the power system. Hence the simulations are developed to reproduce consequences of poor Q allocation among SGs in the plant and to emphasis the drawbacks of manual control. This led to specifying the requirements for coordinated intra-plant Q-V controller which should perform automatic Q allocation among the participating SGs in the plant, according to economic or technical criteria. The solution is based on detailed overview of existing methodologies: i) Q control loop which overlaps the SG terminal voltage control loop introduces undesirable positive amplification [5], [6]; ii) The prototype high side voltage control (HSVC) that regulates transmission voltages by means of SG excitation system [7] doesn't include equal Q allocation at plant level;. iii) The new approach suggested in [5] implies centralized setting of generator' set point values through communication and interface modules for all SGs in the area. This concept which relies on the use of sensitivity matrix concept, is recognized as basis for stable intra-plant Q-V controller. Uniform allocation of Q among the participating SGs in the plant leads to minimization of losses due to reactive current production; uniform aging of the machines; better support to the system voltage profile for slow voltage variations [8], [9]; and better dynamic reactive power support to different perturbations and contingencies in power system.

II. SYNCHRONOUS GENERATOR VOLTAGE CONTROL

The regulation of the voltage within the allowed range is largely achieved through continuous control of SG's reactive

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power production by excitation systems [3]. The Automatic Voltage Regulator (AVR) maintains SG terminal voltage at the reference value over operating range of the SG without operator's action. Reactive current compensation is often implemented in AVR to compensate for a portion of step-up transformer impedance. When reactive current compensation is applied, SGs connected through step-up transformer tend to behave as if their terminals were paralleled/connected to the same busbars. Thus, only part of transformer impedance, up to 70%, could be compensated. A SG is capable of generating and supplying Q within its capability limits defined by D-diagram to regulate system voltage. The Q-V characteristic of a SG equipped with an AVR is shown in Fig. 1. The SG with AVR when working inside the D-diagram operates along curve 2, between the points A and B. When the underexcitation, over-excitation (OEL) or over-current limits are reached, the operating point switches to curves 1, 3 and 4, respectively. Point B determines the point where maximum excitation voltage (Vf_{MAX}) is reached and kept constant in order to prevent overheating of the rotor windings. As illustrated in Fig. 1, starting from point B, any further decrease in terminal voltage will cause Q to decrease. This Q decrease can additionally worsen the situation when the power system is already stressed due to Q deficiency. When AVRs' OELs operate to maintain the SG output within its capability limits, the SG cannot support system voltages any more, and becomes a P-Q instead of PV bus type. Thus the OEL activation is used as one of the impending voltage collapse indicators.

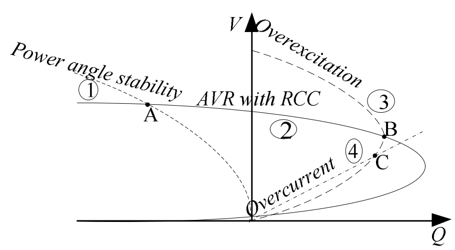

Fig. 1 V-Q capability characteristic for SG with AVR

III. MANUAL Q-V CONTROL IN POWER PLANT PRACTICE

In case of manual Q-V control at power plant, system operator demands by phone the required total Q that plant should deliver at given time. This is usually based on off-line forecasting calculations of dispatching/scheduling of generators which are often different from actual operating condition of the power system. The plant operator should immediately asses required Q contribution by each unit by balancing different technical and economic criteria and give adequate instructions to unit operators to adjust Q output. This is typically done by calling individual unit operators and involves certain time delays. After demanding the Q output from different plants the SO reassesses achieved voltage levels and repeats the procedure (calls individual plant operators) if necessary. It should be mentioned though that the SO's demand for the same Q adjustment within the plant may result in different Q dispatch among the participating generators depending on the actions taken by different plant operators.

The examples of manual control of a SPP's generated Q and HV bus voltage (V_{22}) recorded at a real SPP is illustrated by daily diagram in Fig. 2, Fig. 3 and Fig. 4. The single line diagram of the SPP is shown in Fig. 5. From noon till 4PM, the load in the system is gradually reducing and all voltages, including the HV bus voltage at the point of plant connection (top curve in Fig 2), are rising. The HV bus voltage is regulated partially by the AVRs action, reflected as lower generated Q. At 8:40PM the system operator (SO) demanded to reduce the total generated Q, point 1 in Fig. 2. The SPP operator then dispatched the total Q to participating SG with different time delay, as mentioned above. This delayed action is shown in zoomed detail in Fig. 2. The delay led to Q hunting among the SGs. Point 2 illustrates a decrease in Q generation at the nearby plant resulting from the SO's demand to adjust Q generation in the system. This is followed by a Q generation increase at the observed SPP due to the action of the AVR. Therefore the initially reduced Q output, (point 1) is partly compensated by unwanted actions at point 2. Finally point 3 represents the system operator additional request for Q reduction after observed voltage rise in the power system.

Fig. 3 and Fig. 4 illustrate recorded daily diagrams with manual Q-V control in the SPP performed by two different plant operators. In Fig. 3 operator 1 allocated Q according the units rated power while operator 2, Fig. 4, allocated Q to achieve the same Q distribution (in MVAr). (Note: Depending on network loading and the decision by operator 2 to allocate total Q demand equally among generators may result in

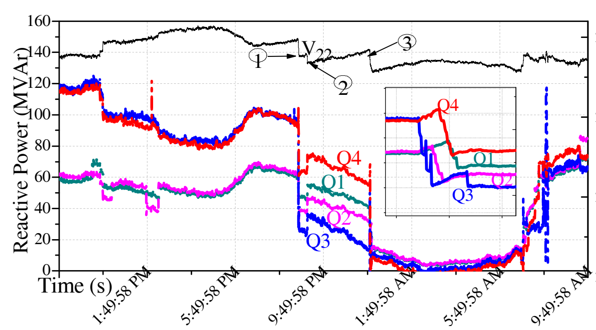

Fig. 2 a) Daily diagram of HV bus voltage and generated Q in SPP (top curve- HV bus voltage; bottom curves – generated Q by individual SGs):1-SO demands reduction of Q according to forecasted daily diagram,; 2-SPP reactive power hunting between electrically close power plants; 3-Additional SO action to compensate for non-forecasted voltage raise

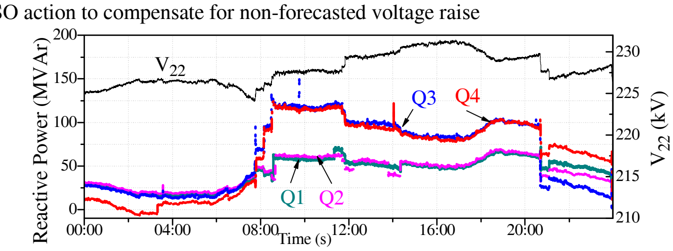

Fig. 3 Daily diagram of A1 to A4 Qs and V_{22} responses under manual voltage references setting by plant operator 1: A1 (cyan solid), A2 (violet dashed), A3 (blue dotted) and A4 (red dashdotted), V_{22} (black solid).

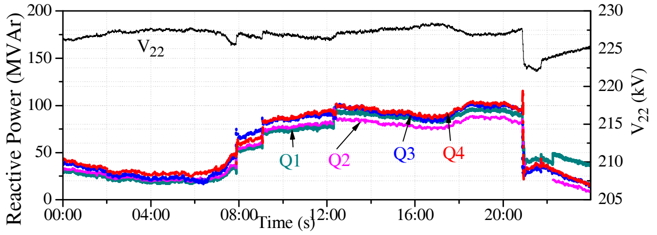

Fig. 4 Daily diagram of A1 to A4 Qs and V_{22} responses under manual voltage references setting by plant operator 2: A1 (cyan solid), A2 (violet dashed), A3 (blue dotted) and A4 (red dashdotted), V_{22} (black solid).

heavily loaded units 1 and 2 with low Q reactive reserve and lightly loaded units 3 and 4 with high Q reserve, thus potentially hitting the OEL by units 1 and 2 during network disturbances). Furthermore, if some equipment in the plant is subjected to a fault or out of service, the plant operator may decide, due to time deficiency, to supply demanded Q difference by increasing Q output of single generating unit and such further increase imbalance in Q generation within the plant.

IV. The Drawbacks of Manual Q-V control in power plant: Case studies

Several case studies are considered here to further highlight potential problems that could occur when manual Q-V control is performed by the plant operator. The test case power plant is a real 1992 MVA steam power plant (SPP) in Fig. 5. The SPP mathematical model [10] developed in the Matlab/Simulink environment to study coordinated Q-V control is used for simulation studies. Case studies are limited to SGs A1 to A4 connected to 220kV busbars.

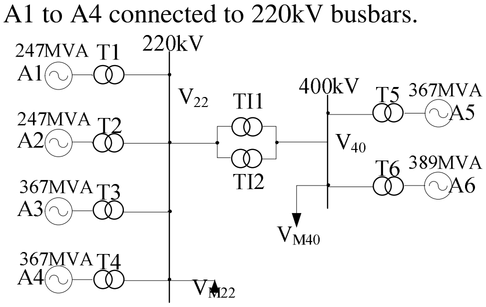

Fig. 5 Single Line Diagram of the Case Study SPP:

In order to reproduce realistic scenario the first operating point is chosen in accordance to actual P dispatch by plant operator and is shown in Table I. The Q_{min} and Q_{max} in Table I are minimum and maximum Qs taken from corresponding SG D-diagram for a given real power (P). (*Note*: The reactive power margin, Q_{margin}, is the distance from the participating generator's Q output to its maximum available Q output, relative to its maximum available Q swing and with respect to its D-diagram and corresponding P generated). The simulations were performed to investigate the SPP response to load changes in the system: the large steps that correspond to major network disturbances (cases I, II and III); the small steps (case IV) that correspond to continuous daily changes in load and the effect of sequential response of plant operator (case V).

Total P and Q generated by the SPP are kept constant but the Q was dispatched differently among participating units in each case. Different step changes (increase) in load were applied at HV busbar and the SPP response to compensate for this change was investigated.

A. *Case I: SPP response to large increase in system load with different Q generation by SGs*

The first operating point, SS1, (Table I) corresponds to the case when two out of four SGs connected to 220 kV bus operate near their maximum Q limits, while the other two are lightly loaded. Fig. 6 shows that during the first two minutes all four units were in the steady state. Then, Fig. 7 shows that while the reactive load was increasing (50MVAr step increases), the voltage at the HV busbar V_{22} was decreasing. This prompted the response from the AVR of each machine.

TABLE I Steady state 1 - SS1

	S(MVA)	P(MW)	Q(MVAr	Q_{min}, (MVAr)	Q_{max}, (MVAr)	Q_{margin} (%)
A1	247	189	140	-10	148	5
A2	247	192	65	-6	146	53
A3	367	283	100	-60	215	42
A4	367	310	195	-55	195	0

As shown in Fig. 7, units A3 and A2 gradually increased their Q as their AVRs tried to keep the terminal voltage V_t of the units at the set value. Units A1 and A4, also gradually increased their Q until the OEL1 and OEL4 were activated at 130s. The OEL2 and OEL3 were also activated 400s later. Segment linearization of HV busbar voltage V_{22} shown in the bottom part of Fig. 7 proves that V_{22} declines faster due to decline in SG V_t after OEL activation. This results in weaker V_{22} support.

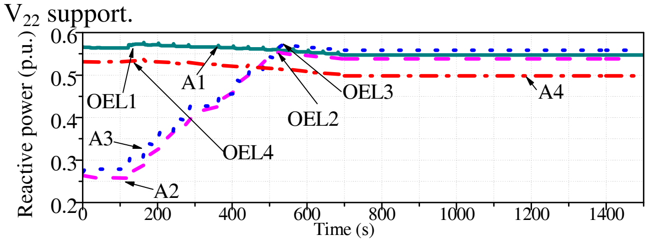

Fig. 6 *Case I*: A1 to A4 Q responses with OEL activation to 50MVAr step increases with A1 and A4 heavily loaded and A2 and A3 lightly loaded: A1 (cyan solid), A2 (violet dashed), A3 (blue dotted) and A4 (red dashdotted)

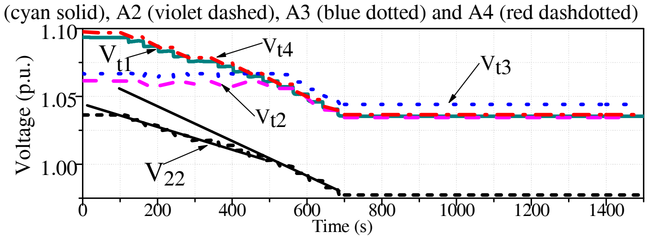

Fig. 7 *Case I* A1 to A4 V_t and V_{22} responses with OEL activation to 50MVAr step increases with A1 and A4 heavily loaded and A2 and A3 lightly loaded: A1 (cyan solid), A2 (violet dashed), A3 (blue dotted) and A4 (red dashdotted)

B. *Case II: SPP response to large increase in system load with equal Q generation.*

In order to prevent the unnecessary and early OEL activation as in *Case I*, the same total Q is dispatched equally in p.u. among SGs. All SGs were producing $Q_{i=1to4}$=0.4 p.u. (base power 367MVA), A1, A2 and A3 were operating at

P=0.77 p.u. and A4 at P=0.85 p.u. (costs of MWh of A1 and A2 is higher than A3 and A4 and A3 has hotspot in stator core so its real power is adjusted to it). Responses to the 50MVAr step increases are shown in Fig. 8. In this case the OEL4 operated first at 320s followed by OEL1, OEL2 and OEL3 at 404s. This case demonstrated that equal Q distribution does not provide the best possible support to the power system when SG are operated at different P since OEL activation (depends on P) transforms the SG terminals from P-V bus type to P-Q bus type thus drastically reduces voltage support from the affected unit (see Fig. 1).

C. Case III: SG voltage support capability as a function of generated real power.

In this case A1, A2 and A4 were generating P as in *Case II* and A3 was generating P3=0.57p.u (two coal mills failure or low coal calorific value). The voltage reference values of A2, A3 and A4 were the same, while A1 was operated near its Q limit. The same load increase as in *Case I* was applied. The results are shown in Fig. 9 and Fig. 10. It can be seen that heavily loaded A4 reached the OEL limit at 398s and lightly loaded A3 at 695s due to its larger Q reserve (according to capability curve). Field voltage responses for all SGs are given in Fig. 10. They show the required field voltage in order to generate a given P and Q. A1's field voltage is high due to large Q and A4's field voltage is high in order to support high P output. It is obvious that at each operating point several factors determine SGs reactive capability which is quite a complex problem for plant operator to deal with on-line.

D. Case IV: SPP response to small increase in system load with equal SGs reactive power reserves

The total P and Q production by SPP was as in the cases I and II. In this case, however, initial Q allocation was set to ensure equal Q reserve of all units (see Table II). It can be seen from Fig. 11 that A1 to A4 give full support to the busbar voltage. The simulation is repeated for differently loaded A1 to A4, Fig. 12. The last two cases which correspond to normal network conditions were simulated to assess voltage support and SPP reactive reserve for different Q allocation. Voltage V_{22} and total SPP Q responses shown in Fig. 12 prove that equal initial reactive reserve Q loading results in much better MVAr and voltage support. This highlights the importance of distribution of Q among the generators in SPP based on equal Q reserve.

E. Case V: The influence of sequential response of plant operator (time delay in setting AVR reference voltage)

Following the total increase in Q of 65 MVAr a manual control was performed by sequential increasing the terminal voltage of units A2 and A3 to restore the voltage at bus V_{22}.

TABLE II STEADY STATE 2 - SS2

	S(MVA)	*P*(MW)	*Q*(MVAr	Q_{min}, (MVAr)	Q_{max}, (MVAr)	Q_{margin} (%)
A1	247	189	110	-10	148	24.5
A2	247	192	108	-6	146	24.5
A3	367	283	148	-60	215	24.5
A4	367	310	134	-55	195	24.5

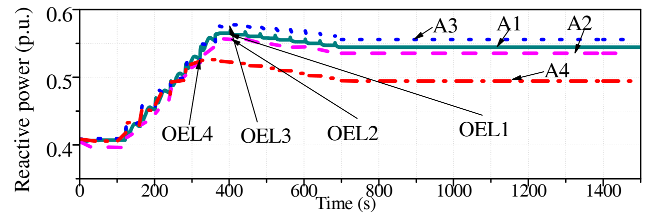

Fig. 8 *Case II*: A1 to A4 Q responses with OEL activation to 50MVAr step increases with A1 to A4 equally loaded: A1 (cyan solid), A2 (violet dashed), A3 (blue dotted) and A4 (red dashdotted)

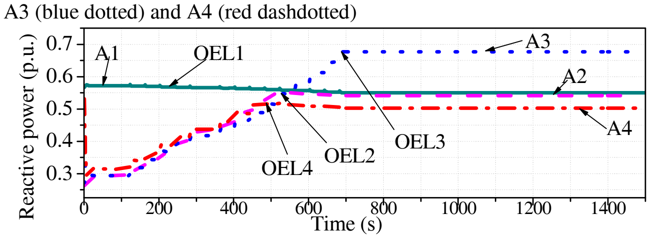

Fig. 9 *Case III*: A1 to A4 Q responses with OEL activation to 50MVAr step increases with A1 to A4 equally loaded: A1 (cyan solid), A2 (violet dashed), A3 (blue dotted) and A4 (red dashdotted)

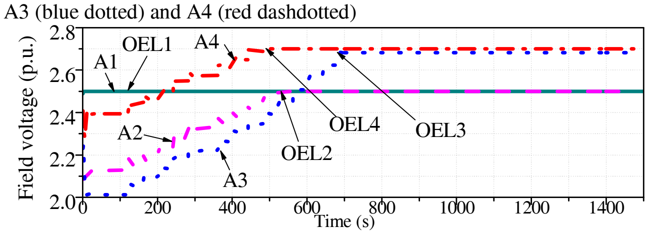

Fig. 10. *Case III*: Field voltage responses of A1 to A4 responses with OEL activation to 50MVAr step increases: A1 (cyan solid), A2 (violet dashed), A3 (blue dotted) and A4 (red dashdotted)

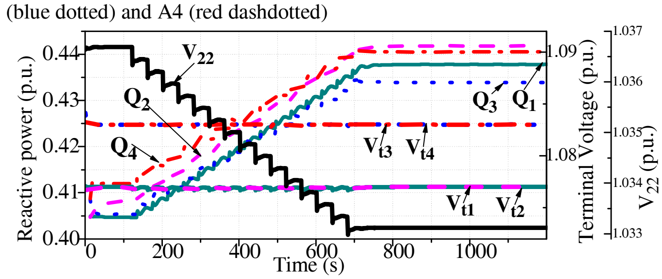

Fig. 11 *Case IV*: A1 to A4 Q, terminal voltage and V_{22} (black) responses to 4.3MVAr step increases with equal reactive reserve at A1 to A4:A1 (cyan solid), A2 (violet dashed), A3 (blue dotted) and A4 (red dashdotted)

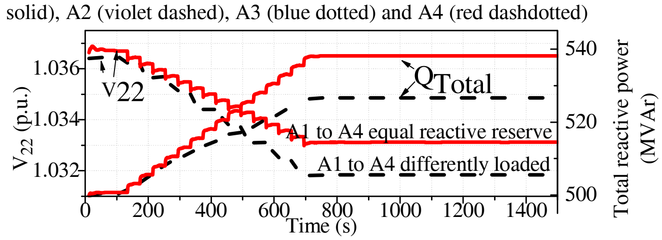

Fig. 12 *Case IV* : HV busbar voltage response and A1 to A4 total Q responses to 4.3MVAr step increases: A1 to A4 with equal reactive reserve (red, solid) and A1 to A4 differently loaded (black dashed)

The reference voltage of unit A3 was increased first, followed by the increase of reference voltage of A2 after two minutes (required for the operator to reassess the voltage level at plant terminals). This resulted in Q hunting between the units A2 and A3, similar to that recorded at the real power plant and shown in Fig. 2. The resulting V_{22} response is shown in Fig. 13 with red, solid line. In practice, the minimum time interval between adjusting the voltage references of two units is from several minutes up to ten minutes depending on the SG dynamics, the locations and distances between the SG control boards. The V_{22} response to simultaneous reference voltage change is shown as a black dashed line. The voltage profiles, shown in Fig. 13, prove that simultaneous SGs actions give better system support than sequential action performed by the plant operator.

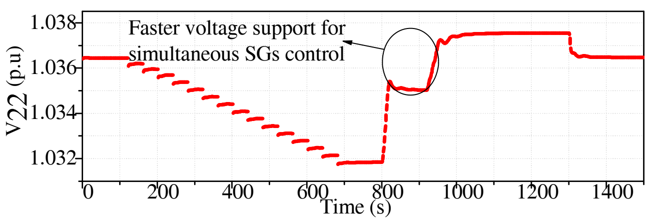

Fig. 13 *Case V*: HV busbar voltage restoration: manually performed by the operator (red, solid), simultaneously performed (black dashed)

F. *Summary of the requirements for enhancing SPP reactive power response and voltage support to the power system by coordinated Q-V control at power plant level*

The main purpose of SPP Q-V controller should be to maintain HV busbar voltage by power plant units in automatic, coordinated and real-time manner. The controller should meet the following requirements: i) Q allocation should be performed according to available Q reserves of individual SGs at particular operating point (to enhance the SPP reactive reserve); ii) HV busbar voltage should be controlled with required droop to avoid (suppress) interactions with the neighbouring plants; iii) It should provide simultaneous reference voltage change since simultaneous SGs actions give better system support without Q hunting.

V. INTRA-PLANT COORDINATED Q-V CONTROLLER - CHALLANGES

The above design requirements are validated in practice by developing intra-plant coordinated Q-V controller (CQVC) for SPP. The performance of the controller is illustrated in Fig. 14. The figure shows the difference in SPP responses under manual and coordinated Q-V control recorded at real SPP following commissioning of the CQVC. The coordinated Q-V control resulted in flatter voltage (V_{22}) and SGs' reactive power responses. Furthermore, the changes in V_{22} that induce changes in Q responses of individual SGs due to AVR action and manual voltage references setting (shown in Fig 3 and Fig. 4) are also corrected by coordinated Q-V control. This effect however, is not illustrated here due to space limitations.

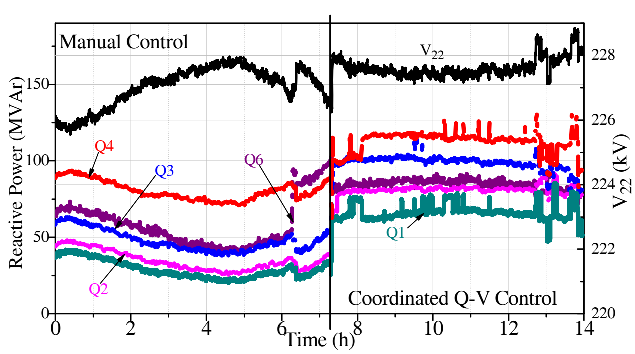

Fig. 14 A1 to A4 and V_{22} responses recorded under manual voltage references setting and Coordinated Q-V control: A1 (cyan solid), A2 (violet dashed), A3 (blue dotted) and A4 (red dashdotted), V_{22} (black solid). A6 response is added since it was temporarily connected to 220kV busbar

VI. CONCLUSIONS

Balancing the reactive power margins, coordination of excitation voltage and limiter settings as well as the simultaneous response of all generators in a power plant gives the best platform for power plant contribution to networkvoltage support. The voltage stability margins are also improved. However, this is not easily achieved through plant operator action when generator voltage references are manually adjusted. By implementing the automatic coordinated Q-V control at power plant level both the power plant and power system would benefit.

SPP Q-V controller maintains HV busbar voltage by power plant units in automatic, coordinated and real-time manner. If the controlled voltage is pilot node voltage rather than HV busbars, this control can be used as a part of broader hierarchical voltage control system. Eventually, if the group of generators are distributed generators, this control can be used in smart grid to achieve desired voltage profiles at LV or MV buses. By continuous regulation of local voltage magnitude by maintaining them within a certain band around set values, under varying loading conditions, power quality is maintained in time. Also the minimization of reactive power losses by locally meeting Q consumption is achieved and corresponding losses reduced.

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