

DISCRETE SHUNT DEVICE BASED VOLTAGE CONTROL IN AN ADJUSTED POWER FLOW SOLUTION

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Abstract: Efficient and effective methods are needed for modeling discrete control actions in an adjusted power flow algorithm. Modeling discrete controls as continuous variables and rounding them off to their nearest steps is not satisfactory for controls with large step sizes such as shunt capacitors and reactors. Such discretization procedures usually off-set the controlled voltages and produce unrealistic power flow solutions. Rigorous formulation of the power flow problem with discrete controls would result in a mixed integer-nonlinear problem which will be difficult to implement. In this paper, a discrete control algorithm is proposed. It can be easily incorporated into any existing adjusted power flow program. This discrete control algorithm has been implemented in a production grade fast decoupled power flow program together with other conventional control adjustments. Test results from a large scale system are promising and the extra computational time is negligible.

Keywords: power flow, adjusted power flow, voltage control, discrete shunt devices

I. INTRODUCTION

Power flow studies are performed in system planning, operations, and control. The solutions are expected to provide information about voltage magnitudes and angles, active and reactive power flows in transmission equipment, and reactive power generated or absorbed at voltage-controlled buses. Engineers and operators can use power flow solutions to investigate the steady-state conditions of the system under a wide variety of postulated situations. The basic power flow solution methods have obtained a fair level of maturity and have overcome some of their earlier limitations in terms of robustness and computation speed [1-4]. However, in order to simulate control strategies of system operations and produce practical solutions, inclusion of automatic control adjustments in the formulation is very important. For the past twenty years, several modeling and computational issues related to these control adjustments have been addressed [5-12]. Unfortunately, the discrete nature of some control equipment is still not modeled satisfactorily. Such discrete controls are widely used by the utility industry. For example, transformers are used for voltage control, shunt capacitors and reactors are switched on or off in order to correct the voltage profile and reduce active power transmission losses, and phase shifters are used to control the active power flows of transmission lines. Correct modeling and efficient implementation of these discrete control adjustments are needed to improve the practical value of power flow solutions.

In most of the existing power flow algorithms, discrete controls are treated as continuous variables until the power flow is converged. Then, they are rounded off to their nearest discrete steps. Simple rounding-off of the discrete controls is an acceptable approximation provided that the discrete steps are small, which is the case with transformers and phase shifters. However, for shunt capacitors and reactors, which have large step sizes, the rounding off approximation may violate desired operation requirements, such as voltage limits. In addition, improper setting of these discrete shunt controls may also cause incorrect solutions for other control variables in the neighborhood area. These deficiencies have to be given sufficient attention.

Exact modeling of discrete shunt controls together with continuous control variables converts the adjusted power flow into a mixed integer-nonlinear problem. Rigorous solutions of such problems are computationally complicated and also very difficult to implement. An alternative would be to incorporate existing operation control practices and perform the required discrete control actions between power flow iterations. In this paper, a discrete shunt control algorithm is proposed. It successfully handles the discreteness of shunt capacitors and reactors during the solution process of an adjusted power flow. This discrete algorithm is consistent with current operational practices and can be incorporated into existing power flow programs in a straightforward manner. It has been implemented in a production grade fast decoupled power flow in the PG&E's Energy Management System. Test results on the PG&E system show that the algorithm provides realistic discrete solutions.

This paper is organized as follows. In Section II, a brief overview of the adjusted power flow solutions is presented. In Section III, existing shunt device based voltage control algorithms are described. In Section IV, the discrete control algorithm is proposed. Some test results carried out on the PG&E network are presented in Section V. Finally, some concluding comments are made in Section VI.

II. POWER FLOW SOLUTIONS WITH ADJUSTED CONTROLS

Power Flow Problem Formulation

The objective of a power flow calculation is to determine the steady-state operating characteristics of a power system for a given set of bus injections. Conventionally, this calculation solves a set of non-linear equations that represent the active and reactive power balance at every bus in the network:

$$\mathbf{G}(\mathbf{x}) = \mathbf{0} \quad (1)$$

where

$\mathbf{G}(\cdot)$ is a non-linear function that represents total active P and reactive Q injections at each bus, and \mathbf{x} is a state vector which consists of bus voltage angles and magnitudes.

Many different solution algorithms have been proposed and implemented [1,2]. The Newton based power flow algorithm with sparsity programming and optimal ordering [3] was suggested in the late 60s. In this method, the partial derivatives with respect to the state variables are taken at each iteration to recalculate the Jacobian matrix. The network sparsity is exploited by ordering techniques and skillful programming. During the early 70s, a so-called fast decoupled power flow algorithm [4] was developed based on the decoupling of the P-Q subproblems in conjunction with some practical assumptions. The algorithm solves a P-Q decoupled power flow problem iteratively with constant coefficient matrices, B' and B'' . The fast decoupled power flow algorithm has geometric convergence rate [4]. Even though it is not as fast as Newton's quadratic rate, its performance is compensated by much higher computation speed for each iteration. Over the years, the fast decoupled power flow has gained wide acceptance in the operational environment, not only because of its simplicity and computational efficiency but also because of its robustness for various system conditions. Recently, some variations of the decoupled formulation have been investigated and proposed to address certain network characteristics [13,14].

Adjusted Solutions

In order to maintain the stability and security of a power system, there are certain operational requirements that have to be met at all times. Some of them can be satisfied by automatic control adjustments. These adjustments are performed at a local level and usually are based on a single criterion. These controls are referred to as *local controls* since there is no global objective function involved in the formulation. The local controls should be modeled in the power flow formulation in order to make the power flow solution realistic and meaningful. Power flow solutions with local control adjustments are called *adjusted power flow solutions*.

Typical local controls in the power flow solutions include phase shifter flow controls, generator local/remote voltage controls, transformer tap controls, shunt capacitor/reactor

controls, etc. [5-12]. In the following, a brief description of these local controls is presented.

Phase shifter flow control aims to control the active power flow through the phase shifter by adjusting its shift angle. Modeling of such an automatic control action requires an additional equation in the formulation. The equation sets the active power flow through the phase shifter to be equal to the desired flow. Alternatively, the control action can be approximated by the linearized sensitivity between the shift angle and the active power flow. After each power flow iteration, the difference between the active power flow and the desired flow through the phase shifter is used to adjust the shifter angle. Adjustments of the angles are then translated into additional injections on the terminal buses. These injections are, in turn, included in the active power mismatches that will be eventually eliminated by the power flow solution process.

Generator local/remote voltage control aims to adjust the MVAR output of one or more generators to control the voltage magnitude of a specified bus. To model this control action, one can either include mismatch equations for voltage and MVAR in the Jacobian, or use error-feedback schemes [10] between the power flow iterations. If at any stage of the solution, a generator reaches its MVAR limit, the *Q-limit control* has to be enforced. The generator then loses its voltage control capability. The Q-limit control, which can also be classified as a local control, aims to enforce the generator MVAR limits when its MW output is determined. Typically the enforcement of the MVAR limits is activated when the power flow solution has moderately converged. Usually the violated PV-bus is converted into a PQ-bus with its MVAR being set at the limit. Careful implementation is necessary to prevent possible oscillations between PQ and PV buses (bus-type switching).

Transformer tap control aims to adjust the tap position of an automatic tap-changing transformer to keep the voltage of a local or remote bus within a desired range. This control is discrete in nature. However, the typical approach is to ignore the discreteness during the adjustment and round off the tap solution to its nearest discrete settings after convergence of the continuous solution has been reached. Then, the power flow is re-solved with the tap settings fixed at their discrete values. Since the discrete steps of transformers are small, this approach is acceptable in practice [15].

Shunt capacitor/reactor control aims to switch on or off capacitor/reactor banks in order to maintain a specified controlled bus voltage within a desired range. In an adjusted power flow, this control is performed using a continuous approximation. The implementation of such continuous approximation is similar to that of the generator voltage control. However, in this case, the shunt admittance is the control variable. The continuous value of the shunt admittance is rounded off to the nearest discrete combination of shunt banks after convergence of the power flow solution has been reached. However, the discrete steps, i.e., the bank sizes of capacitors or reactors are much larger than those of transformers. This discretization

procedure, due to the large MVAR bank sizes, may result in controlled bus voltages being out of their acceptable ranges. Extensive testing with realistic cases has confirmed this claim. Therefore, more accurate modeling is needed to address the discrete nature of the shunt capacitor/reactor controls.

All the local control adjustments can be integrated in the solution process of a Newton formulation and control variables can be solved automatically as part of the solution vector [5-7]. On the other hand, in a fast decoupled power flow, in order to keep the constant B' and B'' matrices symmetric, local control adjustments are usually performed in between or during iteration cycles by simple schemes such as error-feedback or bus-type switching [8-10]. Incorporation of these schemes into an existing fast decoupled algorithm is not expensive. However, all adjustments introduce perturbations during the iterative process. If the adjustments are introduced at an inappropriate time during the iterative process or in an incorrect sequence, they may prolong the convergence of the power flow solution. Furthermore, interactions between different local controls may lead to hunting that can cause oscillations during the solution process, or even divergence.

Over the years, many implementation techniques have been proposed to improve the adjusted solution in the power flow algorithm. It is our belief that adjusted power flow algorithms, if properly implemented, can produce robust solutions.

III SHUNT DEVICE BASED VOLTAGE CONTROL

As mentioned in Section II, shunt capacitor and reactor banks are switched on or off to maintain a specified controlled bus voltage within a desired range. Voltage regulation is usually performed to provide a better voltage profile of the system under different loading conditions. The desired voltage ranges are usually determined based on operators' experience and standard practices. In the field, when a controlled bus voltage falls below the desired low limit, either shunt reactor banks will be switched off or shunt capacitor banks will be switched on to bring the controlled bus voltage up within its range. When the voltage is too high, either capacitor banks will be switched off or reactor banks will be switched on to bring down the voltage. These control actions are performed based on a single criterion, i.e. enforcement of the controlled bus voltage limits. No global reaction is considered in the determination of these control actions. Usually, there are no specific rules that determine the proper switching sequence. The switching of any given shunt device is not dependent on the status of any other shunt device of the same type controlling the same bus voltage. In PG&E, as a general rule, the capacitor and reactor banks controlling the same bus voltage cannot be energized simultaneously, regardless whether they are connected to the same bus or not. In other words, all reactor banks must be switched off before any capacitors can be switched on; similarly, all capacitor banks must be switched off before any reactors can be switched on. Usually, this is also a standard practice in the utility industry. The Vaca-Dixon station of PG&E clearly

demonstrates this point. This station contains three-winding transformers, with shunt reactor banks connected to the tertiary windings, i.e. a 13.8-kv bus. Shunt capacitor banks are connected to the 230-kv bus. For normal operation, the voltage is monitored at the 230-kv bus and the shunt devices are used to maintain a desired voltage range. These reactor and capacitor banks will not be switched on simultaneously.

In an adjusted power flow solution, the shunt device control action is usually modeled as a simple relationship between the reactive power of the shunt devices and the controlled bus voltage. The reactive power in such formulation is a *continuous* variable. Furthermore, there is no specific model for the representation of either the capacitor or the reactor bank. In other words, the operation rules are transparent to the power flow solution algorithm.

In the presence of shunt devices, the reactive power mismatch equation of the controlling bus i, i.e., the bus which the shunt devices are connected to, should be rewritten as:

$$\Delta Q_i = \sum Q_i + Q_{sh} \quad (2)$$

where

$\sum Q_i$ represents the total fixed reactive power generation and load at bus i, and Q_{sh} is an additional state variable that represents the shunt reactive power amount.

For the controlled bus j, a voltage mismatch equation is introduced as:

$$\Delta V_j = V_{sp} - V_j \quad (3)$$

where

V_{sp} is the specified voltage for bus j, and V_j is the voltage at bus j.

In practice, the shunt devices may not be connected to the controlled bus directly, i.e., bus is not necessary the same as bus j. In addition, V_{sp} in (3) is usually chosen such that

$$V_{sp} = (V_{spL} + V_{spH})/2 \quad (4)$$

where

V_{spL} is the lower limit of the desired voltage range, V_{spH} is the upper limit of the desired voltage range.

Equations (2) and (3) can be easily integrated into the Newton power flow solution process.

An alternative approach in providing a shunt device based voltage control in an adjusted power flow solution is to implement an approximation scheme between power flow iterations. After each iteration, the controlled bus voltage is monitored. When the voltage is outside its desired range, the shunt admittance is updated. An effective update rule is the error-feedback scheme [10]. In such scheme, the linear feedback-gain is the sensitivity, s_{ij} , between the controlled bus voltage, V_j , and the shunt admittance, b_i (i.e. $s_{ij} = \delta V / \delta b_i$). In other words, the shunt admittance adjustment required to bring the controlled bus voltage, V_j , within its limits is calculated by

$$\Delta b_i = \Delta V_j / s_{ij} \quad (5)$$

The sensitivity, s_{ij} , can be calculated by computing specific element in the inverse of B'' matrix of the fast decoupled power flow (or the Jacobian matrix of the Newton power flow). The desired correction term, ΔV_j , in (5) is determined by (3).

The shunt admittance change, Δb_i , will cause an incremental mismatch $\Delta b_i \cdot V_i \cdot V_i$ at bus i , where V_i is the voltage at the controlling bus. This mismatch is then included in the reactive power mismatch equation (2) in the subsequent iteration. The B'' matrix is also modified to reflect the change of the shunt admittance.

Both methods will reach a continuous solution when the power flow converges. Then, the solution is rounded off and fixed to the nearest discrete bank size settings. The power flow is then re-solved with the fixed shunt device settings. Since the bank sizes are usually large, there is no guarantee that the final controlled bus voltages will still fall within their desired ranges. Furthermore, reactor and capacitor banks controlling the same bus voltage may be switched on by the algorithms simultaneously, if they are not connected to the same bus. These problems may potentially degrade the practical value of the adjusted power flow solutions.

IV. DISCRETE CONTROL ALGORITHM

Formulation of the Problem

In order to provide practical solutions that reflect both the discreteness of the shunt devices and the operational rules, a *discrete* switching algorithm that is consistent with standard practices has to be incorporated into the adjusted power flow algorithm. However, exact modeling of discreteness into the Jacobian matrix is not trivial. An alternative is to implement a discrete algorithm between power flow iterations, similar to the error-feedback scheme described in the previous section. Such a discrete algorithm is proposed in the following.

After each iteration of the power flow solution process, the controlled bus voltage is monitored. Then, the control variables are adjusted accordingly. In this case, the adjustments are performed based on the switching on and off the shunt banks. To be precise, if $V_j > V_{spH}$, then the total reactive power from the controlling shunt devices (including possibly shunt reactors and capacitors) has to be reduced. Based on specific operational rules, the algorithm will either switch off capacitor banks or switch on reactor banks, depending on their statuses from the previous iteration. If $V_j < V_{spL}$, then the algorithm will switch off reactor banks or switch on capacitor banks. If $V_{spL} < V_j < V_{spH}$, no action will be taken. As can be seen in this formulation, there is no continuous approximation. When the adjusted power flow solution converges, the shunt devices are solved at their discrete bank sizes.

This formulation can incorporate standard operation practices. Some of these practices include : (a) reactor and

capacitor banks controlling the same bus should not be energized simultaneously, (b) any combination of the same type of shunt devices (either reactor or capacitor banks) can be switched, (c) separate desired voltage ranges can be assigned to reactor and capacitor banks controlling the same bus, etc.

Algorithm

A discrete control algorithm based on the formulation above has been developed. The algorithm is general enough so that it can be implemented between power flow iterations of any existing solution method, such as Newton or fast decoupled power flow.

There are two major parts of the discrete control algorithm: (a) the *input processing*, and (b) the *control adjustment*.

Input Processing

For each controlled bus, perform steps A1 to A7 as follows:

Step A1: Collect all shunt devices (i.e. reactor and capacitor banks) that control the same bus voltage.

Step A2: Sort the shunt devices by bank size. The sorted list of all reactor banks will precede the sorted list of all capacitor banks.

Step A3: Calculate all unique MVAR combinations of reactor banks and store them as negative MVAR segments.

Step A4: Calculate all unique MVAR combinations of capacitor banks and store them as positive MVAR segments.

Step A5: Assign the desired voltage ranges for reactor and capacitor banks.

Step A6: Sort the MVAR segments created in steps A3 and A4, from the most negative MVARs (reactor combinations) to the most positive MVARs (capacitor combinations).

Step A7: Go to step A1 for the next controlled bus.

When the above process is completed for all controlled buses, then perform steps A8 and A9:

Step A8: Set the initial MVAR segment pointer for each controlled bus equal to its initial MVAR value.

Step A9 : Start the next power flow solution iteration.\

Control Adjustment

At the end of each power flow iteration, the following control adjustment steps are performed for each controlled bus:

Step B1 : Determine whether the control adjustment will be performed on the bus based on the power flow convergence condition at a given iteration (see Rule 1 later). If YES,

then continue. If NO, then go to the next controlled bus.

Step B2 : Determine the desired voltage range based on the type of shunt device that will be used for the adjustment, either reactor or capacitor. If the solved voltage from previous iteration is within the range, then go to step B5. Otherwise, continue to the next step.

Step B3: Calculate the sensitivities of the voltage at the controlled bus to all shunt devices controlling that bus (when it is necessary).

Step B4: Move the MVAR value segment to the direction of adding MVARs to the system, if the controlled bus voltage is below its lower limit based on the voltage range chosen in step B2. Otherwise, move to the direction of removing MVARs from the system, if the controlled bus voltage is above its upper limit. Determine the changes in shunt statuses for each segment change and calculate the changes in voltage for moving to the new segment. Continue the process until the voltage resides within the range, or until the last segment in that direction is reached. The sensitivities calculated in step B3 are used to calculate approximate voltage changes.

Step B5: Go to step B1 for the next controlled bus.

When the above process is completed for all controlled buses, then perform steps B6 and B7.

Step B6: Include the resultant MVAR injections from step B4 for the shunt devices into the corresponding reactive power mismatch equations for the subsequent power flow iteration.

Step B7: Continue to the next power flow iteration. Two rules are implemented to facilitate the performance of the control adjustment algorithm:

Rule 1: The control adjustments will not be activated until the power flow has moderately converged. Specifically, only when the largest reactive power mismatch in the system is less than a user defined tolerance, the control adjustment algorithm above will be executed. In our implementation, the local convergence concept [16] is used. When the largest reactive power mismatch in the system is less than a certain tolerance, say ϵ_1 , and the mismatch corresponding to the controlled bus is less than the convergence tolerance, say ϵ_2 (and $\epsilon_1 > \epsilon_2$), then the discrete control adjustments will be performed on that bus.

Rule 2: To prevent possible oscillations, a counter is assigned to each segment in step B4. When the control adjustment moves into a specific segment, the counter for that segment will be increased by one. Once the counter reaches a pre-set value, the voltage control of this bus will be disabled for subsequent power flow iterations. This protective logic is similar to the safeguard used for the bus-type switching in the Q-limit control process [10].

Limitations

The proposed discrete control algorithm can be easily incorporated into any adjusted power flow algorithm. In PG&E, it has been implemented in an adjusted fast decoupled power flow algorithm used in the Energy Management System. The power flow solution contains all the local control adjustments mentioned in Section II except that the shunt capacitor/reactor control is performed based on the proposed algorithm. In our particular implementation, the algorithm still has the following limitations which, for all practical purposes, are acceptable

(a) Usually many combinations of the shunt devices that provide the same amount of reactive power correspond to the same MVAR segment. The algorithm in its current form will not be able to distinguish one combination from the other. Only a specific combination among them will be suggested by the solution. To eliminate this arbitrariness, additional operational guidelines are needed to be included in the algorithm.

For example, assume there are three 10-MVAR reactors, R1, R2, and R3, connected to the same bus and controlling the same bus voltage. The algorithm will switch on, say, R1 whenever it needs to reduce 10 MVARs and never R2 or R3. Similarly, R1 and R2 will be switched on if 20 MVARs have to be subtracted from the bus injection and never R1 and R3, or R2 and R3.

(b) If shunt devices are connected to different buses, the MVAR segment suggested by the algorithm may not represent the most effective shunt combination required to control a bus voltage. For example, assume there are two parallel three-winding transformers, TR1 and TR2, each with reactors connected to the tertiary windings. There are three switchable 10-MVAR reactors on transformer TR1's tertiary winding and two switchable 15-MVAR reactors on TR2's tertiary winding. These reactors are controlling the bus voltage on the secondary side. If the algorithm determines that a reduction of the reactive power by 30 MVARs is required, the reactors on transformer TR2 will be switched on (because of the smaller number of banks in TR2) even though the reactors on transformer TR1 may be more effective in controlling the controlled bus voltage according to the calculated sensitivities.

V. TEST RESULTS

The proposed discrete control algorithm has been implemented in a fast decoupled power flow program together with all the conventional local control adjustments mentioned in Section II. The new adjusted fast decoupled power flow has been extensively tested on several different cases of the PG&E system.

The network model used in the testing consists of 1700 buses with 1400 buses modeling the internal system and 300 buses modeling the equivalent of the external companies of the Western System Coordinating Council (WSCC). The 500-kv, 230-kv, and 115 -kv transmission network and all generation facilities in the internal system are modeled in detail. The subtransmission systems, i.e., 60-kv and below, are modeled as static loads. The total

reactive power available consists of 1,941 MVARs coming from shunt reactors and 9,983.5 MVARs coming from shunt capacitors. Currently, there are 29 switchable shunt reactor banks on tertiary windings, i.e., 13.8-kv windings of three-winding transformers (500/230/13.8-kv) with 45 MVARs per bank. There are 26 switchable shunt capacitor banks with either 63, 50, or 38.4 MVARs being connected to either 230-kv, or 115 -kv buses.

One of the main operational concerns regarding discrete shunt controls is at the Vaca-Dixon and Tesla stations of the PG&E network. In both stations, the shunt devices have relatively large bank sizes. Both Vaca-Dixon and Tesla stations contain three-winding transformers, with four shunt reactor banks (45 MVARs per bank) connected to the 13.8-kv winding and four capacitor banks (63 MVARs per bank) connected to the 230-kv bus. These shunt devices are used to control the voltage of the 230-kv bus. Based on experience, the switching of one bank can possibly cause 1 to 3 kv difference on the monitored 230-kv bus voltage. Especially during peak load conditions, it is not unusual to experience at least 2 kv difference in Tesla for an additional capacitor bank. The substantial voltage fluctuation at these stations is a cause of concern, since the controlled bus voltage may easily be pushed outside its desired range. This real-life example indicates that continuous approximations of such discrete controls in adjusted power flow solutions are not adequate.

The impact of continuous approximations on the power flow solutions and the benefits from the proposed discrete algorithm are clearly shown in Table 1 and 2. Both tables illustrate the power flow solutions for the Vaca-Dixon and Tesla stations using three different methods to model shunt controls.

S_a represents the solutions using the proposed discrete control algorithm, as described in Section IV; S_b represents the solutions with the shunt controls being modeled as continuous variables without any rounding-off, as discussed in Section III; and S_c represents the solutions that are computed in two steps : (a) rounding off the continuous solutions, S_b , to their nearest steps after convergence of the first power flow, and (b) solving a second power flow with the controls fixed at their discrete settings.

For the first case in Table 1, the voltage limits at the controlled buses are 231kv and 233kv. For the second case in Table 2, the limits are 228w and 230kv. The fast decoupled power flow iterations, solved controlled bus voltages, and solved shunt device MVARs are presented. In both test cases, the total system load is 18,620 MW; the power flow convergence tolerances are 1MW/1MVAR; the shunt control starting tolerance, ϵ_1 , is 500 MVARs and the local convergence tolerance, ϵ_2 , is 5 MVARs.

Table 1: test results with desired voltage range 231 kv - 233 kv

CASE 1: 231kv - 233 kv		Sa	Sb	Sc
# of FDPF iterations		15P/ 18Q	10P/ 10Q	11P/ 11Q
solved kv	Vaca-Dixon	231.8	231.7	231.6
cap. MVARs		128.0	169.6	189.0
reac. MVARs		0.0	-23.3	-45.0
solved kv	Tesla	232.1	231.1	violation <u>230.8</u>
cap. MVARs		189.0	150.7	126.0
reac. MVARs		0.0	0.0	0.0

As can be seen from the test results, the solutions from S_a and S_c can have one to two banks difference. When the proposed discrete control algorithm is used, the solved controlled bus voltages are always within the desired ranges. However, some of the solved voltages in the solution S_c violated their limits. More importantly, in both cases, some reactor banks are switched on together with capacitor banks since solution S_c considers only net MVARs. This is not consistent with standard operational practices. On the contrary, solutions produced with the proposed algorithm are always realistic. Furthermore, improper discrete solutions from rounding off shunt devices can adversely affect other control variables, such as SVCs or LTCs in the neighborhood of these shunt controls. The combined effect will degrade the practical value of the adjusted power flow algorithms.

Table 2: test results with desired voltage range 228 kv - 230 kv

CASE 2: 228kv - 230 kv		Sa	Sb	Sc
# of FDPF iterations		12/ 12Q	10P/ 10Q	13P/ 16Q
solved kv	Vaca-Dixon	229.2	229.4	violation <u>231.4</u>
cap. MVARs		0.0	102.2	189.0
reac. MVARs		0.0	-104.2	-45.0
solved kv	Tesla	229.1	230.0	violation <u>232.0</u>
cap. MVARs		0.0	150.7	126.0
reac. MVARs		-90.0	-116.9	-45.0

The proposed algorithm has minimal impact on the overall convergence of the adjusted power flow. As can be seen from Tables 1 and 2, and from many other tests not reported here, the increase in the number of iterations in the

solution S_a is not significant. CASE 1 represents an extreme case in which additional iterations are due to Q-limit controls and bus-type switching.

VI. CONCLUSION

A discrete control algorithm, which effectively handles the discrete shunt controls in the adjusted power flow solution, has been presented. It is consistent with standard operational practices and performs exact discrete adjustments between power flow iterations. This algorithm can be easily merged with any existing power flow algorithm. In PG&E, it has been implemented in an adjusted fast decoupled power flow. Test results indicate that the solutions are practical and the controlled voltages are guaranteed to be within their desired ranges unless MVAR limits are reached. The extra computational time required is negligible.

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