On Complexity Reduction of Voltage Stabilization MPC Schemes by Partial Explicit Feedbacks

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***Abstract*— In this paper voltage stabilization of power systems is considered. The proposed control approach relies on using at the lower level local feedback strategies to update the OLTC setpoints and a receding horizon global controller at the higher level to update the reactive power injections and load shedding. The combinatorics associated to the capacitors and load shedding discrete inputs are partially alleviated by using an efficient parametrization technique. Simulations are carried out on a benchmark power system to further illustrate the approach.**

I. Introduction

In the last decade, the power community has shown a great interest in systematic design methods for assessing stability in power networks. Voltage instability is undeniably one of the most inconstant and costly failures, for instance, the 14 August 2003 blackout in North America cost between US $4 billion and $6 billion [1]. Basic material on voltage stability philosophical concepts may be found in the recent surveys [2], [3]. The interested reader may also consult [4], [5] for general definitions and basic problems.

Much of the work reported on voltage stability assessment relies on heuristics, where basically, knowledge of the system and experience gained by the designers is put forward. Schemes such those developed in [6] where heuristics based load shedding strategies are compared with branch and bound based ones. The multi step design consist in time domain simulation for generating training scenarios. An optimization soundstage is then carried out to minimize the amount of load shedding with respect to the value found in the training set.

Another family of methods relies on computing a security margin or distance to voltage collapse, see e.g, [7] for a survey. Based on these measures, sensitivities with respect to the different control actions are then computed. These provide directions towards the control must be updated, this is in general followed by a constrained multiple optimization stage for dispatching the different control actions, see e.g, [8]. In the same spirit, [9] use a quasi steady state simulation approach. A simple formula is then proposed to update the different control actions based on off line bus ranking, see also [10] and [11] for other variants. In [12] a clear distinction is made between the different control actions and a scheme is derived where corrective and preventive control strategies interact, the first is used in extreme contingencies (loss of system solvability) while the latter is for enhancing the system stability margin.

The method developed in this paper fall into the category where knowledge of the system is reduced at its basic. Only a simulation model is indeed needed. This model should incorporate at least the dominant features i.e, the load dynamics since voltage collapse is driven by these dynamics. These approaches include mainly methods based on predicting and analyzing sensitivities of the system trajectories see e.g, [13] where this is discussed in the more general framework of hybrid systems. See also [14] where a predictive control approach based on evolutionary programming techniques is discussed. The predictive control approach is also exploited in the work [15]-[16] where an improved *depth first* search method from the Artificial Intelligence community is used as an alternative to further reduce the combinatorics. Basic material on predictive control can be found in [17], [18].

The aim of the present paper is to explore a particular controller design methodology for voltage collapse avoidance in power systems with emphasis on a particular benchmark problem [19]. This is a step towards a fully coordinated centralized solution in the spirit of [20], where the focus is on area central controller. We will not deal with higher level controllers used to coordinate areas controllers, indeed we believe that at a higher level an expert system with advanced heuristics shall be used, the interested reader may consult the multi agent approaches e.g, [21], [22]. The proposed approach relies on a decomposition strategy. The power system is decomposed into regions, in each region a local controller is implemented to update the internal variable i.e, the transformers turn ratio. At the higher level a global predictive strategy is in force to activate the power injections and load shedding. At this stage, a simple open loop parametrization together with an efficient ordering technique are proposed to alleviate the associated combinatorics.

The paper organization is as follows : section 2 presents a brief description of the benchmark power system and the complexity related to a full predictive scheme. Section 3 is devoted to the control approach formulation, a complexity study is also included. In section 4, relevant simulation results are included. Finally, some conclusions and future work orientations are given in section 5.

II. Benchmark presentation

The following section is a brief presentation of the ABB medium scale benchmark, the reader is referred to [19] for a more detailed description. The power system motivating the study is the one depicted in figure 1. It is composed of the

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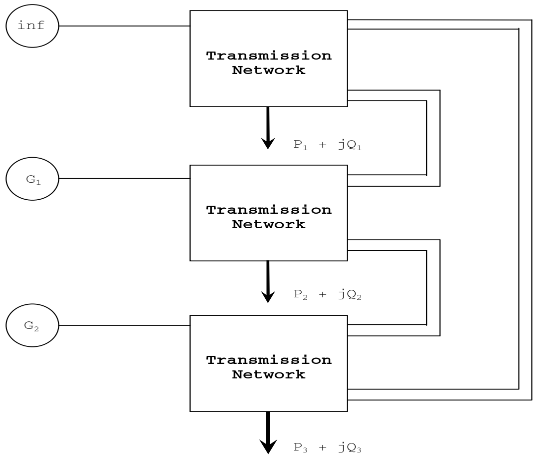

Fig. 1. The ABB medium scale benchmark

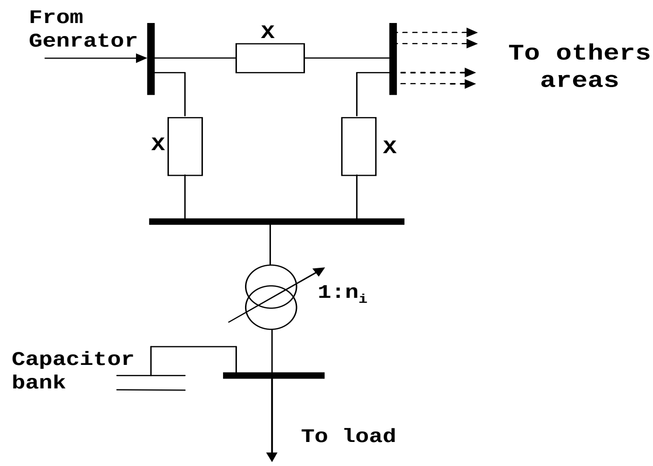

Fig. 2. Transmission network in the ABB medium scale benchmark

following elements

- Two generation elements. These are modelled as a set of algebraic equations due to the wide discrepancy between the voltage collapse and the generators time constants.
- An infinite bus, used to represent the rest of the network.
- Three interconnected areas represented by the transmission network blocks.
- Three double transmission lines modelled as pure reactances, denoted as $X^{i_3}_{i_1 i_2}$ where the subscripts i_1 and i_2 refer respectively to the departure and arrival areas and the superscript i_3 the line index $i_3 = 1, 2$. Due to inter-area faults, these parameters may undergo sudden changes.

In figure 2 is depicted the content of the transmission network block. Initially a network of this type was proposed as a benchmark [23] and solutions were proposed by the different project partners. In [24] the nonlinear hybrid dynamics are converted to a Mixed Logical Dynamical system by finely approximating the nonlinearities. A predictive control strategy is then developed to stabilize the power system. On the contrary no preliminary approximation stage is required for the approach developed in [25] where an efficient open loop parametrization is shown to give satisfactory results with highly reasonable computation times.

The network block is composed of the following components

- Three transmission lines modelled as constant pure reactances X.
- A transformer equipped with an *On Load Tap Changer* OLTC. The state graph in Figure 3 illustrates the function of a typical OLTC control system. The automata has three possible states labelled as, *Wait*, *Count* and *Action* state
  - Wait state: the automata is in this state as long as the condition $|v_i - v_{r_i}| \leq \Delta$ is satisfied where v_r is the continuous control input to the OLTC, v_i the load voltage, Δ is a positive real threshold and i is the area index $i \in \mathcal{I} = \{1, \ldots, l\}$ ($l = 3$ for the case study)
  - Count state: while the automata is in this state, a timer T_{count} is activated and if it exceeds a certain value T_d (typically $30sec$), the automata passes to the next action state
  - Action state: a control action is taken, the turn ratio n_i is one-step increased (or decreased) if the threshold Δ is over (under) exceed, i.e.

$$n_i^+ = \begin{cases} n_i^- + dn & if\ v_{r_i} - v_i > \Delta \quad and\ n_i^- < n_{max} \\ n_i^- - dn & if\ v_{r_i} - v_i < -\Delta \quad and\ n_i^- > n_{min} \end{cases} \quad (1)$$

where the superscript $-$ and $+$ represent respectively the instants just before and after the update, dn is the tap changer increment ($dn = 0.02$)
- A reactive power source represented by the capacitor banc b_i. This is actually the second control input of the transmission network.
- A nonlinear load with recovery dynamics described by the following first order differential equation [26], [23]

$$\dot{x}_i = -\frac{x_i}{T_{p_i}} + P_{0_i}(\sqrt{v_i} - v_i^2) \quad (2)$$

and the following output equations representing respectively the absorbed active and reactive power

$$P_i = (1 - k_i)\left(-\frac{x_i}{T_{p_i}} + P_{0_i} v_i^2\right) \quad (3)$$

$$Q_i = (1 - k_i)(\alpha_i P_i) \quad (4)$$

where x_i is the $i - th$ load internal state, T_{p_i} is a time constant P_{0_i} and $\alpha_i = cst_i$ are respectively the steady state active power and constant power factor. The variable k_i represents the load shedding percentage, allowing a higher level controller to disconnect a part of the load. Actually, the third control input of the network transmission.

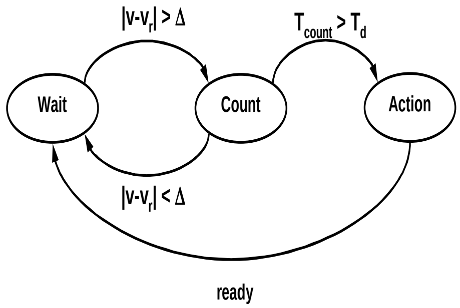

Fig. 3. The OLTC dynamics

The control inputs can be grouped in the following continuously valued vector

$$u_c = (v_{r_1} \dots v_{r_l})^T \tag{5}$$

and discretely valued one

$$u_d = (b^T \ k^T)^T \tag{6}$$

with $b^T = (b_1 \dots b_l)$, $k^T = (k_1 \dots, k_l)$. The power system can thus be written in a compact *Differential Algebraic* form

$$\dot{x} = f(x, v, \theta) \tag{7}$$

$$0 = g(x, v, \theta, u_c, u_d) \tag{8}$$

where $x = (x_1, \dots, x_l)$ and $v = (v_1, \dots, v_l)$ is the loads voltage vector, θ groups the different network parameters i.e, lines reactance among others. The vector field f describes the load dynamics and g the network topology (power flow equations).

A. Complexity of a full predictive control solution

Nonlinear predictive control is now widely recognized to be a feedback strategy providing a relatively easy handling of both nonlinearities, constraints and optimality concerns. Recall that predictive control schemes amount to compute at each sampling time jT_s (j is a nonnegative integer and T_s is the sampling period) an optimal open-loop control sequence (in the sense of some given cost functional), to apply the first part of the resulting optimal open-loop control sequence until the next sampling instant. At the next sampling instant, the whole problem is re-considered on a moving-horizon basis and the procedure is repeated resulting in a state feedback law. For long prediction horizons N_pT_s ($N_p \in \mathbb{Z}^+$), this may lead to open loop optimal control problems with a high dimension of the decision variable. In fact this is the case for the problem under study. To further illustrate, let us consider the general case where l similar areas are interconnected. Suppose that all of these regions are equipped with the same control elements b_i and k_i under the constraints

$$k_i \in \mathcal{K} = \{0, 1, \dots k_{max}\}, \quad i \in \mathcal{I} = \{1, \dots, l\} \tag{9}$$

$$b_i \in \mathcal{B} = \{0, 1, \dots b_{max}\} \tag{10}$$

Since the state automata describing the OLTC is invertible, one can considers directly that the control input to the power system is the transformer turn ratio n_i [25], [24] and since only three moves are allowed (see Equation (1)). The complexity of a receding horizon approach for a fixed prediction horizon N_p is bounded by the following

$$\mathcal{C}_{full} = [3 \times (k_{max} + 1) \times (b_{max} + 1)]^{l \times N_p} \tag{11}$$

For the benchmark under consideration, $k_{max} = 2$, $b_{max} = 1$ and $l = 3$, this gives the upper bound $[18]^{3 \times N_p}$.

The complexity can be reduced by introducing explicit feedback strategies to update some internal variables. In this contribution a simple feedback law is introduced to update the voltage reference to the OLTC. The feedback is based on a direct inversion of the discrete dynamics and on the assumption that the transformer turn ratio is used to enhance the voltage level while the reactive power injections and load shedding are responsible for restoring an equilibria. More advanced heuristics or analytical design can be used to update these variables for purposes other than voltage enhancement, e.g, local control Lyapunov functions have been also used in [27].

This has the drastic effect to reduce the complexity by a factor of $3^{l \times N_p}$, giving the following complexity

$$\mathcal{C}_1 = [(k_{max} + 1) \times (b_{max} + 1)]^{l \times N_p} \tag{12}$$

That is still dependent on the prediction horizon N_p. Next, an open loop control parametrization together with an efficient ordering technique are introduced to further reduce the combinatorics. The control approach is detailed in the next section.

III. The control approach

A. A local feedback strategy

The local feedback strategy used in this work is based on the assumption that the sensitivity matrix of load voltages with respect to the tap changer positions is positive definite [28]. This means that the tap changer is used as a voltage enhancement control action, allowing an achievement of a higher equilibria. While a global predictive strategy is used as a corrective action for updating the capacitor and load shedding values. Indeed, the corrective action allows the movement of unsolvable point (voltage collapse) to the closest equilibria satisfying certain criteria, then the tap changer action is used to achieve a higher voltage stability level.

Starting with the update equations of the OLTC

$$n_i^+ = \begin{cases} n_i^- + dn & if \ v_{r_i} - v_i > \Delta \quad and \ n_i^- < n_{max} \\ n_i^- - dn & if \ v_{r_i} - v_i < -\Delta \quad and \ n_i^- > n_{min} \end{cases} \tag{13}$$

In order to increase the load voltage, one needs to augment the value of the turn ratio n_i. It is then sufficient to take for v_{r_i}

$$v_{r_i} = (v_i + \Gamma\Delta), \quad \Gamma > 1 \tag{14}$$

to make active the first part of (13). The same reasoning, leads for the case where a voltage decrease is needed to the following

$$v_{r_i} = (v_i - \Gamma\Delta) \tag{15}$$

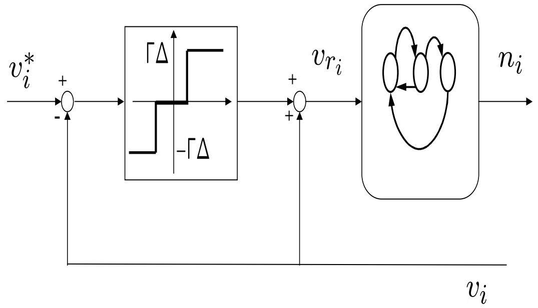

Fig. 4. The local feedback strategy for updating the OLTC reference

By combining equations (14)-(15) and introducing an exogenous signal v_i^* the following update equation is obtained

$$v_{r_i} = (v_i + \Gamma\Delta sgn(v_i^* - v_i)) \quad (16)$$

where v_i^* is a voltage target equilibria associated to the $i-th$ area and $sgn(\cdot)$ is the usual sign function.

The target voltage v_i^* needs not be a true equilibria of the system (a true equilibria will need a preliminary power flow analysis, not necessary in this case). Thus, in most cases exact tracking of v_i^* can not be achieved. A dead zone is then introduced i.e, the value of the turn ratio is blocked whenever the voltage enters the dead zone. The bloc diagram is shown in figure 4.

Recall here that a more sophisticated scheme is to use a feedback from exogenous signals to increase the dead zone or flip it whenever respectively tap locking or reversing is required. This scheme will be also useful if the local controller is used as a corrective control action see e.g, [29] and [30].

B. The predictive control strategy

In this section, we present the global feedback strategy used to update the values of the bank capacitor and load shedding. Let us consider a power system composed of l areas. Each area is indexed from 1 to l and equally equipped with a capacitor bank b_i and load shedding mechanism k_i.

$$k_i \in \mathcal{K} = \{0, 1, \dots k_{max}\}, \quad i \in \mathcal{I} = \{1, \dots, l\} \quad (17)$$
$$b_i \in \mathcal{B} = \{0, 1, \dots b_{max}\} \quad (18)$$

Let us briefly recall some notations, b, k and v denote respectively the vectors of capacitor values $(b_1, \dots b_l)$, load shedding $(k_1, \dots k_l)$ and load voltages $(v_1, \dots v_l)$. The control input vector is $u_d^T = (b, k)$. The control is implemented in a sampling scheme with a sampling period $T_s = T_d$ (the counter threshold in the OLTC), the control input is given at each sampling instant jT_d where j is a nonnegative integer as

$$u_d(j) = \begin{pmatrix} b(j) \\ k(j) \end{pmatrix} \in \mathcal{B}^l \times \mathcal{K}^l \quad (19)$$

where the sets $\mathcal{B}$ and $\mathcal{K}$ are defined above. Let $\tilde{u}_d(j)$ denotes the open loop control profile at the instant jT_d over the prediction horizon N_p

$$\tilde{u}_d(j) = (u_d(jT_d), \dots, u_d((j + N_p - 1)T_d)) \quad (20)$$

Let us also denote by $\mathcal{U}_d$ the set of admissible open loop control profiles, then the following set of constant admissible profiles is introduced as

$$\mathcal{U}_d^{(\bar{b},\bar{k})} = \{\tilde{u}_d \in \mathcal{U}_d \mid \tilde{u}_d \equiv (\bar{b}, \bar{k})\} \quad (21)$$

where $(\bar{b}, \bar{k}) \in \mathcal{B}^l \times \mathcal{K}^l$. Let us also define the set of load shedding vectors with equal components as

$$\mathcal{K}_o = \{\bar{k} \in \mathcal{K}^l \mid \bar{k}_1 = \bar{k}_2 = \dots = \bar{k}_l\} \quad (22)$$

Meaning that load shedding is equally distributed among the areas, and that they are equally treated. Then an ordering map is defined on the set $\mathcal{K}_o$ as

$$\mathcal{O} : \mathcal{K}_o \longrightarrow \{1, 2, \dots, card(\mathcal{K})\} \quad (23)$$

such that

$$\{\bar{k}^{(1)} \geq \bar{k}^{(2)}\} \Longleftrightarrow \left\{\mathcal{O}(\bar{k}^{(1)}) \geq \mathcal{O}(\bar{k}^{(2)})\right\} \quad (24)$$

Let the set $\mathcal{S}_{nc}$

$$\mathcal{S}_{nc} = \Big\{(\bar{b}, \bar{k}) \in \mathcal{B}^l \times \mathcal{K}_o \mid \forall \tilde{u}_d \in \mathcal{U}_d^{(\bar{b},\bar{k})} \; : \; v(\cdot; x_0, \tilde{u}_d) \text{ is defined over } [0 \;\, N_p\tau]\Big\} \quad (25)$$

be defined as the set of capacitors with minimum load shedding vector such that 'no voltage collapse is induced'. Here $v(\cdot; x_0, \tilde{u})$ represents the load voltages vector under the constant profile $\tilde{u}_d$ and the load states initial condition $x_0 = x(0)$. Next a subset of S_{nc} is defined as

$$\mathcal{S}_f = \{(\bar{b}, \bar{k}^*) \in \mathcal{S}_{nc} \mid \bar{k}^* = \arg \min_{\bar{k} \in \mathcal{K}_o, \forall \tilde{u}_d \in \mathcal{U}_d^{(\bar{b},\bar{k}^*)} \;,\; v_{N_p}(x_0, \tilde{u}_d) > \underline{v}} \mathcal{O}(\bar{k})\} \quad (26)$$

where $v_{N_p}(x_0, \tilde{u}_d)$ represents the voltage vector at the final prediction instant N_pT_d. Note the value of minimum load shedding can be different in the two sets S_{nc} and S_f as defined in (25)-(26) and that $S_f \subseteq S_{nc}$ since the control pair that satisfies the terminal inequality does not induce a voltage collapse. The following quadratic performance measure is then introduced

$$J = \int_0^{N_pT_s} (v(\tau) - v_{ref})^T P (v(\tau) - v_{ref}) d\tau \quad (27)$$

where P is a positive definite matrix of appropriate dimensions and v_{ref} is a vector containing the voltage references to the power system. Recall here no penalty terms are needed neither on the control inputs nor on the terminal voltages since respectively an ordering technique (23) is already in force and a terminal inequality is embedded in (26). Taking constant open loop control profiles leads to a complexity that is independent of the prediction horizon. The full complexity $\mathcal{C}_{full}$ is further reduced by a factor of $[(k_{max} + 1) \times (b_{max} + 1)]^{N_p}$ leading to the following

$$\mathcal{C}_2 = [(k_{max} + 1) \times (b_{max} + 1)]^l \quad (28)$$

Remark 1: Recall that a key feature in receding-horizon control is that the resulting closed-loop control is much more rich than the underlying open-loop parametrization. The consequence of this is that in many cases, apparently over-simplified open-loop parameterizations results in a sufficiently rich closed-loop control behavior.

Next, the algorithm is summarized as

ALGORITHM

Step 1 Compute the set S_{nc} of capacitors $\bar{b} \in \mathcal{B}^l$ with minimum load shedding $\bar{k}^* \in \mathcal{K}_o$ such that no voltage collapse occurs during the prediction horizon N_p.

Step 2 Compute the set $S_f \subseteq S_{nc}$ such that the voltages at the terminal prediction horizon satisfy the constraint $v_{N_p} \geq \underline{v}$.

Step 3 Among all the possibilities compute the minimum of the performance index J in S_{nc} **if** $S_f = \emptyset$ **else** in S_f. Denote the minimizing pair by $(\bar{b}^*, \bar{k}^*)$.

Step 4 $s := l$, $B := \mathcal{I}$.

Step 5 **if** ($\bar{k}^* \neq \arg\min(\mathcal{O}(\bar{k}))_{\bar{k} \in \mathcal{K}_o}$ **and** $B \neq \emptyset$) **then**

- Enumerate all the possible values of the load shedding vectors k with variable Hamming distance h from $\bar{k}^*$, $h = 1, \ldots s-1$ and such that $\bar{k}_i \in \{\bar{k}_i^*, \bar{k}_i^* - 1\}$, $\forall i \in B$. $\bar{k} := \bar{k}^*$.
- Compute the new $\bar{k}^*$ such that J is minimized and B as $\{i \in B : \bar{k}_i \neq \bar{k}_i^*\}$. $s := card(B)+1$ Goto **Step 5**.

end if

Step 6 Apply $(\bar{b}^*, \bar{k}^*)$ and Goto **Step 1**.

1) Algorithm complexity: In step 1, the set S_{nc} is computed by a simple enumeration. Since in most cases the number of possible values for the capacitor bank is less than the possibilities offered by the load shedding inputs. This enumeration needs

$$\mathcal{C}_{step1} = card(\mathcal{B})^l \times card(\mathcal{K}_o) \tag{29}$$

evaluations over the prediction horizon at most (since the open loop control profiles are taken constant). The Step 2 needs no particular computations since the inclusion relation $S_f \subseteq S_{nc}$ is satisfied all the time. Step 3 needs a direct comparison of at most $\mathcal{C}_{step1}$ values of the performance index J. Step 5 generates all the vectors with a Hamming distance ranging from 1 to $card(B)-1$. Where the Hamming distance is defined as the number of elements of two vectors that disagree. The algorithm is best understood in the light of the simple example depicted in figure 5. Suppose that at the initial stage $\bar{k}^* = (333)$ (represented by a white node) is the minimum value of the load shedding such that the constraints defined by the set S_f or S_{nc} are fulfilled. At the following stage we generate all the vectors with Hamming distance 1 and 2 ($h = 1 \ to \ card(B) - 1$). For this stage, only

$$\begin{pmatrix} 2 \\ 3 \end{pmatrix} + \begin{pmatrix} 1 \\ 3 \end{pmatrix} = 6 \tag{30}$$

nodes are checked, these are depicted in gray. Suppose that the new minimizing vector is $k^* = (322)$, this gives a number

$$\begin{pmatrix} 2 \\ 2 \end{pmatrix} + \begin{pmatrix} 1 \\ 2 \end{pmatrix} = 3 \tag{31}$$

nodes to visit. And the process is continued until no further values for the load shedding are available. This is what the if bloc is dedicated to. The complexity in terms of visited nodes in the general case is at most

$$\mathcal{C}_3 = \sum_{m=1}^{l-1} \begin{pmatrix} l \\ m \end{pmatrix} + (\bar{k}_i^* - 1) \sum_{m=1}^{l-1} \begin{pmatrix} l-1 \\ m \end{pmatrix} = \bar{k}_i^*(2^{l-1} - 1) \tag{32}$$

instead of

$$\mathcal{C} = (\bar{k}_i^* + 1)^l \tag{33}$$

for an exhaustive exploration. Where $\bar{k}_i^*$ is any component of the vector $\bar{k}^*$ at the first stage, e.g, $\bar{k}_i^* = 3$ for the example in figure 5. In table I is shown a comparison in terms of visited nodes between an exhaustive search and the proposed ordering technique for the example in figure 5 for a variable number of areas.

number of areas	exhaustive	proposed
2	16	4
3	64	12
4	256	28
5	1024	60

TABLE I

COMPARISON BETWEEN THE EXHAUSTIVE SEARCH AND PROPOSED APPROACH

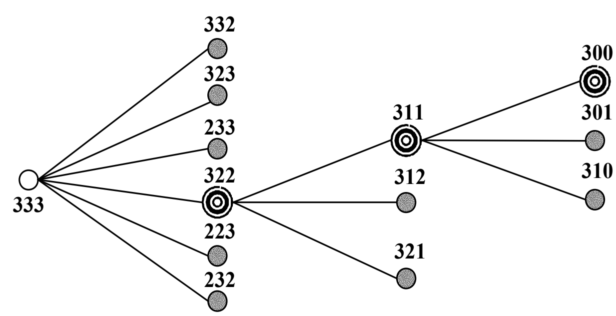

Fig. 5. Search algorithm, in gray : searched nodes. In black : winner nodes

IV. SIMULATION RESULTS

V. CONCLUSION

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