Configurable, Hierarchical, Model-based Control of Electrical Distribution Circuits

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***Abstract*— Grid modernization strategies often focus on replacing aging distribution control equipment with state-of-the-art devices capable of remote monitoring, communication, and control. However, wholesale replacement of the existing distribution infrastructure may not be practical or economical. Additionally, even with improved capabilities, "smart" devices may still be ignorant of changes in circuit topology. This paper presents a model-based distribution control scheme that is independent of circuit topology and integrates legacy and modern control equipment. Simulation results indicate the proposed method can improve circuit performance under both normal and abnormal conditions.**

***Index Terms*— power distribution control, power systems modeling, power system simulation**

I. Introduction

As the existing distribution infrastructure ages and demand growth continues to approach system limits, utilities are looking for methods to more efficiently operate distribution systems and to reliably supply increasing load with existing infrastructure. Recent industrial and governmental interest in constructing a “Smart Grid” recognizes these limits and seeks to remedy problems associated with the aging electrical infrastructure using advanced metering and control strategies.

In addition to distribution systems becoming capacity constrained, more and more power sources are being connected to the distribution systems. Plug-in hybrid electric vehicles, renewable resources such as wind and solar, storage, and other types of distributed generation are requiring distribution circuits to operate in ways they were not originally designed to operate.

Historically, operating criteria for distribution systems are maintained by independently acting control devices. The set points for these control devices are generally based on one or two loading conditions and are often not actively updated. Device set-points sometimes need to be de-tuned to prevent “hunting” between control devices. As a result, distribution circuits can be operating inefficiently for much of the year.

Many research efforts have focused on improving distribution system control. Optimal capacitor placement and scheduling [1] can increase the efficiency of distribution circuits by pre-processing the circuit conditions, typically a day ahead, and establishing hourly set-points.

In [2] the authors analyze interactions between distributed generation and capacitors. An algorithm is presented which factors the variable real and reactive injections from distributed generation in an optimal capacitor scheduling problem.

Reference [3] explores coordinating multiple control devices to satisfy a set of weighted objective functions. The authors use a Genetic Algorithm to sort through possible solutions of a balanced, radial feeder, implementing several strategies based on different weighting criteria. The Genetic Algorithm solution was used due to the large number of possible solutions of the constrained combinatorial optimization problem.

More recently, approaches have suggested the use of multi-agents to perform distribution automation [4],[5]. Such approaches involve the use of distributed intelligence to manage the behavior of different elements of the distribution system such as generation and customer response.

Additionally, many "Smart Grid" efforts have been aimed at improving distribution system operation through greater utilization of emerging technologies such as advanced metering and distributed generation [6]. References [7].[8] describe Volt / Var management systems for "Smart Grid" distribution application.

Several new control features are considered here that have not been considered in previous work. The features that distinguish this work for previous efforts include the following:

- Incremental improvement - the controller does not seek a global optimal, but rather improves the current operating point through repeated execution, a simplification which allows for real-time application while still providing benefit to the utility.
- Automatic device discovery - distribution circuit topology will change, drastically at times. Faults and subsequent sectionalizing device operations can separate a control device from its nominal circuit design configuration. The controller in this work not only detects when a device is lost, it detects when new devices are attached to a distribution circuit via reconfiguration.
- Automatic control set-point adjustment - circuit reconfigurations can alter the effectiveness of control devices. After reconfiguration, the controller

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automatically adjusts the dispatch of control devices to reflect the current circuit topology.

- Fully coordinated control - the controller provides a framework to fully coordinate all control devices found on the distribution system.

Furthermore, a successful control strategy needs to be aware of all active control devices on a circuit. A tendency in modernization and “Smart Grid” implementations is to replace legacy equipment with new devices that have communication and control capabilities. It is unreasonable to expect utilities to replace their entire infrastructure overnight. The control strategy described here provides a means to seamlessly integrate modern “smart” equipment with legacy equipment.

This paper investigates a Configurable, Hierarchical Model-based Controller (CHMC) to improve distribution system efficiency and capacity. Configurable refers to the ability of the CHMC to automatically adapt to changes to the circuit as well as the ability to adjust parameters in the controller to improve performance and accuracy.

As a hierarchical controller, the CHMC automatically discovers control devices inserted into the circuit model, determines if they can be used in the control decision, and dispatches set-points to the local controllers of active control elements. The algorithm automatically adjusts to new circuit topologies and coordinates different types of control devices to provide an improved operating point relative to a set of prioritized objective functions.

The CHMC considered here performs steady state control. That is, during a control interval the circuit is assumed to be operating at steady state and the CHMC determines controls that improve efficiency, capacity, and/or voltage regulation without violating operating constraints. Also, instead of controlling variable values at a single location in the circuit, values to be controlled are determined by considering values throughout the circuit. The exact calculations are discussed below.

II. CONTROLLER DESIGN

A. *Integrated System Model and Graph Trace Analysis*

One of the major challenges of model-based control is the difficulty associated with creating and maintaining a model that accurately represents the system. Integrated System Models (ISM) can help solve this problem by encouraging the different groups within a utility to develop and maintain a single model. This means that Operations works with the same model as Relaying, Maintenance, and Planning, and that the model contains all of the information necessary for these different areas to perform their respective duties.

ISM based models have been used at Detroit Edison for supervisory control of Distributed Generation (DG) [9]. The DG model-based control receives start of circuit phase current measurements and adjusts the power flow calculations so that the results of the power flow match the circuit measurements [10]. The model is then used to predict low voltages or overloads throughout the circuit. If such limit violations are discovered, then the model is used to calculate generation injections that would eliminate the violation.

Graph Trace Analysis (GTA) is built upon a combination of ideas from physical network modeling, graph theory, and generic programming [11-13]. The ISM used in this work uses GTA to manage the topology. The CHMC described uses GTA to implement the automatic device discovery, detect topology changes, and determine device usability.

B. *Control Algorithm*

The CHMC uses an iterative approach to incrementally improve the performance of the circuit. One of the main difficulties of optimal distribution system control is the extremely large number of possible combinations of control device states. The CHMC in this paper is designed around 3 distribution system properties that are used to limit the number of states for control devices during any given control interval. These properties are:

1. A globally optimal circuit state is difficult to consistently attain in practice due to significant delays associated with control device movement and the constantly changing load profile of a given circuit.
2. It is desirable to minimize the movement of control devices; therefore, a solution in the vicinity of the current operating point is preferred to a solution far away from the current operating point.
3. Some control actions are mutually exclusive. For example, switching multiple capacitor banks at the same time should generally be avoided.

With these properties in mind, the CHMC attempts to use the available control devices to find a solution close to the current operating point that improves a set of prioritized operating criteria. If a better operating point is found, the controller provides a signal to the local controller of the devices that need to be moved. The search window can be adjusted, but a tradeoff exists between the exhaustiveness of the solution search and computation time.

Fig. 1. illustrates the control algorithm. First, the CHMC automatically discovers all control devices on a circuit. In the initial design the types of controllers are limited to switched shunt capacitors, voltage regulators, and DGs; however, the control algorithm can be extended to other types of control devices. The CHMC uses the circuit model to find control devices on the circuit for analysis as well any circuits that can be attached to the test circuit via sectionalizing devices.

The discovered control devices are categorized as either usable or unusable. For instance, a control device placed in manual control would be unusable. Usable devices are the set of control devices the CHMC can manipulate. Unusable devices cannot be adjusted by the CHMC; however, the controller must be aware of unusable devices because they will respond to changes made to usable control devices.

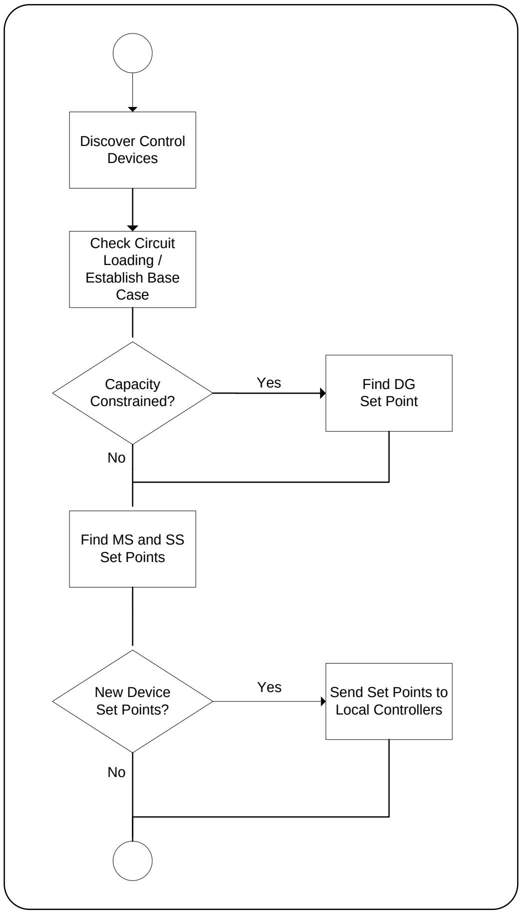

Fig. 1. CHMC algorithm flow diagram

The ability to model both usable and unusable devices gives the CHMC flexibility. Not only can the CHMC provide a more accurate solution by including the affects of unusable devices in the control algorithm, but the ability for usable and unusable control devices to coexist gives a utility flexibility to incrementally upgrade their system when most convenient or cost effective.

The controller places usable control devices into one of three categories:

- **Singe Step Devices** such as Switched Shunt Capacitors often have a dramatic impact on the system when operated. For this reason, no two single-step devices are operated in the same control iteration.
- **Multi Step Devices** such as Voltage Regulators do not drastically affect the circuit when they operate for a single step.
- **Distributed Generation** (DG) can behave as SS or multiple-step devices. Because DGs often have a minimum power output requirement, they behave as single-step device when being turned on or off. However, once connected to the grid they behave more like a multiple-step device.

Once the devices are discovered and categorized, the CHMC checks the loading on the circuit to determine if the circuit is capacity constrained. If the circuit is capacity constrained, the CHMC attempts to use any DG on the circuit to alleviate the constraint. The DG is dispatched prior to other devices because, since it can behave as a single-step device, a turn-on or turn-off operation would eliminate all other control device operations, thus dramatically decreasing computational load for that iteration. Additionally, DG are more effective than other control device at alleviating capacity constraints.

The current implementation of the CHMC does not use cost functions to determine the output of the DG. Instead, the CHMC assumes that the DG output should be minimized and therefore dispatches DG at the lowest value which minimizes the capacity constrained cost function discussed below.

After the DG output is determined, the CHMC tries to use the multiple-step and single-step devices on the circuit to find a better operating point. The first priority of the CHMC is to maintain voltage criteria on the distribution circuit. Since the controller is model-based, the voltage (V_i) at every customer meter can be estimated using relatively few measurements on the circuit. The estimated voltages include distribution transformer, secondary, and service voltage drops. The Voltage Deviation Total (VDT) criteria is calculated by

$$VDT = \sum V_D$$
$$V_D = \begin{cases} V_i - V_{UB} & V_i > V_{UB} \\ 0 & V_{UB} \geq V_i \geq V_{LB} \\ V_{LB} - V_i & V_i < V_{LB} \end{cases} \qquad (1)$$

where

V_i = Customer level voltage
V_{UB} = Voltage upper bound
V_{LB} = Voltage lower bound

The VDT is a measure of the overall voltage regulation of the circuit. For the purpose of this paper, the upper and lower voltage boundaries were set according to ANSI C84.1 [12] Range A Service Voltage levels for systems less than 600 V, specifically 114 V to 126 V on 120 V base. Using a deviation total allows the CHMC to factor in both the number and severity of voltage violations on the circuit.

The second priority of the controller is to alleviate capacity constrained components. The controller looks at the remaining current capacity (C_i) of all devices on the primary of the circuit (distribution transformers and secondary connections are neglected). If any device has a remaining capacity below a threshold, the controller will try to alleviate the capacity constraint. Equation 2 describes the Weighted Capacity Total (WCT). Additionally, the voltage criteria associated with the VDT can be relaxed during capacity constrained operation. For this paper, the ANSI 84.1 Range B Service Voltage levels were used under capacity constrained operation. The WCT is given by

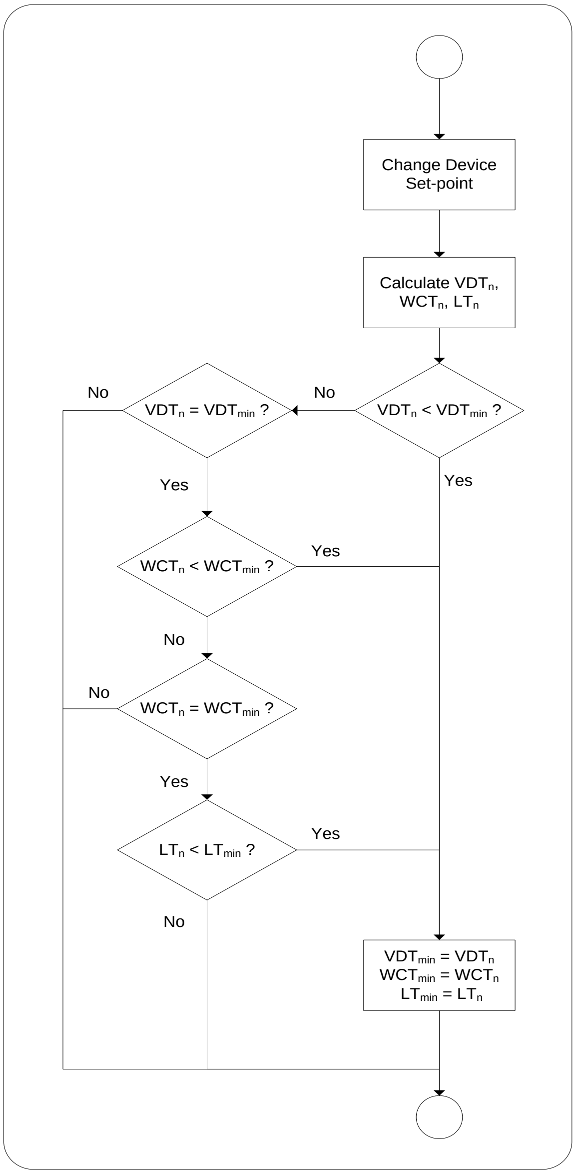

Fig. 2. CHMC decision structure

$$WCT = \sum C_D$$

$$C_D = \begin{cases} C_L - C_i & C_i < C_L \\ k(C_L - C_i) & C_i < 0 \le C_L \\ 0 & C_i \ge C_L \end{cases} \tag{2}$$

where

C_i = Remaining capacity on a primary component

C_L = Remaining capacity limit

k = Scaling factor for over loaded components

Some consideration was given to how the VDT and WCT were tabulated. It is common to use a sum of deviations squared approach when tabulating metrics such as the ones listed above. In this case, the sum of deviation approach was used because it provides balance between the severity of the excursion and the number of excursions. A sum deviations squared approach significantly weighs the severity of the excursions over the number of excursions.

Lastly, the controller tries to reduce the losses on the system. The Loss Total (LT) is given by

$$LT = \sum P_{Loss_i} \tag{3}$$

where

P_{loss_i} = Real loss of each component

The LT reflects losses from the secondary of the substation transformer to the customer meter.

It is important to note that the algorithm is not limited to maximizing efficiency as the third objective. Any parameter or combination of parameters can be substituted. Additionally, since a search algorithm is used, the solution is limited only by the successful convergence of power flow. Therefore, with a robust power flow the same CHMC algorithm could be used on any distribution topology (radial or networked).

Fig. 2 describes the CHMC decision path. The CHMC uses a set of nested priorities to ensure a more efficient operating point is not attained at the expense of service quality. In other words, a more efficient operating point is only considered if the voltage and capacity violations are at their minimum levels. This decision path is described in detail below.

The state of the circuit when the CHMC begins is treated as the base case. Minimum values for VDT, WCT, and LT are initialized to the base case values ensuring a solution always exists. The CHMC then iteratively searches for a better solution in the neighborhood of the base case.

For each iteration *n*, the set-points of control devices are moved and VDT_n, WCT_n, and LT_n are recalculated and compared against the minimum values. Since VDT has highest priority, any solution greater than VDT_{min} is rejected and any solution less than VDT_{min} is accepted without checking the WCT or LT. If VDT_n is equal to VDT_{min}, WCT_n is tested.

Similarly, if the WCT_n is greater than WCT_{min} the solution is rejected and if WCT_n is less than WCT_{min}, the solution is accepted without checking LT_n. If WCT_n equals WCT_{min}, the decision structure is repeated for the LT_n.

If LT_n is less than LT_{min} the solution is accepted. By nesting the objectives instead of weighting them, the CHMC ensures the voltage and capacity criteria are strictly enforced.

When a solution is accepted, the set-points are saved and VDT_n, WCT_n, and LT_n replace the minimum values. At the end of all control iterations the solution corresponding to the minimum values is transmitted as local set points to the control devices unless the minimum solution is the base case. If any or all communications fail, then he control devices continue to operate with the last set point that they received, which corresponds to the solution that is used today.

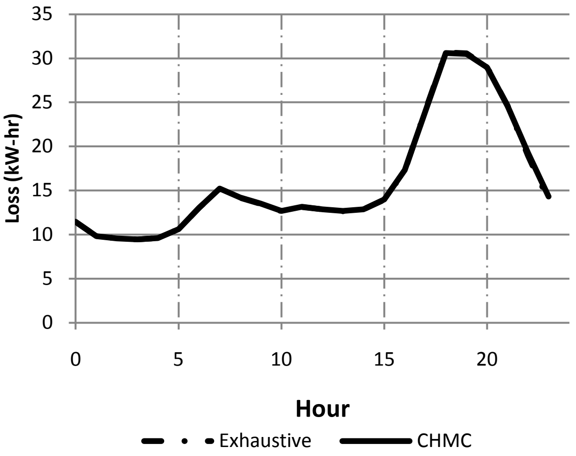

Fig. 3. Comparison with optimal solution

TABLE I
COMPARISON WITH OPTIMAL SOLUTION

	Total Loss (kW-hr)	Max VDT	Max WCT	Computation Time (s)
CHMC	384.93	17.76	0	1
Exhaustive	383.61	16.81	0	1,303

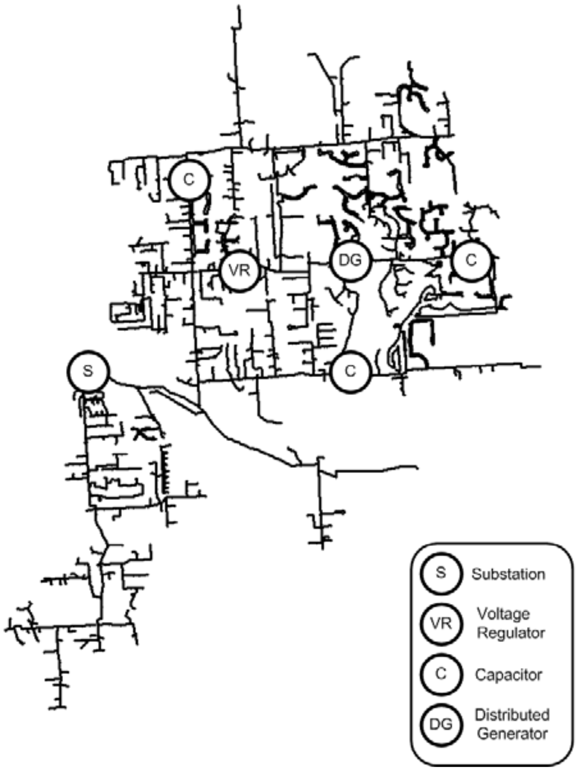

Fig. 4. Test Circuit

III. SIMULATION RESULTS

A. Comparison with optimal solution

Though the CHMC is not designed to find a globally optimal solution, simulations were performed to give some indication of how well the CHMC performs versus the globally optimal solution. A test circuit was constructed which simulated a residential circuit with a gang-operated switched shunt capacitor and a set of independently operated voltage regulators. The test circuit is simple enough to allow an optimal solution to be found via exhaustive search.

Fig. 3 shows the results of the hourly simulations, and Table I gives the detailed results. The CHMC solution lies directly on top of the optimal solution for much of the day. From these simulation, it is clear that the CHMC can provide results that are reasonably close to optimal for residential circuits. Additionally, the CHMC solved in 1 second, while the exhaustive search took 1,300 times longer to execute.

B. Test circuit

The circuit for testing the CHMC is illustrated in Fig. 4. It is a 13.2 kV, Y-connected circuit with a largely residential customer base and a 16 MVA peak load. This circuit was the subject of a recent study performed for NREL, the California Energy Commission, and the Department of Energy[13].

Fig. 4 shows the test circuit model. The circuit model includes multi-phase, unbalanced loads. The time varying loads are based on customer billing information, load research data, and hourly measurements from primary customers. Fig. 5 shows the feeder load profiles for the heavily loaded and lightly loaded days. Hourly load profiles are used for the simulations in this paper.

The test circuit contains 3 sets of switched shunt capacitors, 1 set of voltage regulators, and a 1 MVA synchronous DG. The capacitors are gang operated and ordinarily controlled via a time clock. Under normal control, the voltage regulators operate on voltage control based on a local voltage measurement. The DG is typically operated as a peak shaving unit. The real power output of the generator is set to maintain a particular current set point at the substation, in this case regulating to 650 A at the feeder exit cable. In the work here the circuit operations are simulated with these controllers and the results compared with the CHMC controller performance.

The test circuit also has 8 adjacent circuits which can be switched onto the test circuit via sectionalizing devices. The adjacent circuits contain 19 control devices, 16 sets of switched shunt capacitors and 3 voltage regulators.

C. Normal operation

Figure 6 shows simulation results for a heavy load day and Fig. 7 shows simulation results for a light load day. Figures 6 and 7 show both the normal controls and CHMC controller performance. The top graph shows the loss and the middle graph shows the remaining capacity for the circuit by hour of day. The bottom graph of each figure shows a load duration curve for each day where the feeder load is sorted from the highest load to the lowest load. By coordinating the control devices, the controller is able to reduce the losses on the

TABLE II
SIMULATION RESULTS FOR HEAVY AND LIGHT LOAD DAYS

Heavy Load Day			
	Normal Control	**CHMC**	**Improvement**
Losses	8,199 kw-hr	7,854 kw-hr	4.2 %
Maximum Feeder Load	14,341 kVA	14,146 kVA	1.4 %
Max VDT	316.2	284.9	9.9%
Max WCT	139.8	117.4	16.0%
Feeder Usage	283,004 kw-hr	271,705 kw-hr	4.0%
Generation	6,933 kw-hr	9,522 kw-hr	-37.3%
Average Min. Capacity per Phase	9.9 %	11.1 %	1.2 %

Light Load Day			
	Normal Control	**CHMC**	**Improvement**
Losses	5,649.10 kw-hr	5335 kw-hr	5.6 %
Maximum Feeder Load	11,987 kVA	11,206 kVA	6.5%
Max VDT	60.3	40.4	33.0%
Max WCT	0	0	0 %
Feeder Usage	221,386 kw-hr	206,057 kw-hr	6.9%

system and increase the remaining capacity while maintaining voltage criteria on the circuit. Table II gives a comparison between the normal control and CHMC for both heavy and light loading conditions. Table II shows losses for the day, maximum feeder load, and feeder usage, as well as generation and performance metrics.

When the circuit is heavily loaded or capacity constrained, the CHMC has less flexibility to find set-points that improve the system efficiency due to loading and customer voltage limitations. Even with these limitations, the CHMC is able to improve the losses during the heavily loaded day by more than 4%. Much of the improvement may be attributed to the increased DG output. Additionally, the CHMC is able to reduce the peak demand on the circuit by 1.4% and reduce total feeder energy usage by 4%.

The Average Minimum Capacity per Phase shown in Table II refers to the average of the minimum capacity for each phase that occurs on the primary of the circuit during the test period. The minimum phase capacity does not necessarily occur at the same time for each phase.

When the circuit was lightly loaded, the CHMC was able to improve losses by 5.6%. The load duration curves of Fig. 6-7 shows the CHMC was able to lower the feeder load throughout the entire day. This reduction in load was due to reduced losses and operation of the DG.

D. Automatic Device Discovery

Because the adjacent circuits have control devices that could be switched onto the test circuit, the CHMC needs to be aware of these control devices. For this simulation, all control devices attached to the circuit are assumed potentially usable by the CHMC. Realistically, a control device that is switched over from another circuit may not be usable; however, the CHMC must account for these control devices since their operation will impact the circuit performance.

For simplicity, the system was reduced to the test circuit and one adjacent circuit containing a switched shunt capacitor bank. The circuits were reconfigured such that the capacitor bank from the adjacent circuit was disconnected from its nominal design circuit and connected to the test circuit.

Table II (I don’t believe this table is shown. Should this be Table III???) shows the results of the CHMC device discovery algorithm before and after the reconfiguration. For capacitors, Set-point 1 refers to the low voltage set-point (turn on) and Set-point 2 refers to the high voltage set-point (turn off). For voltage regulators, Set-point 1 refers to the voltage set-point and Set-point 2 refers to the bandwidth. Under the normal configuration the CHMC detects the capacitor bank on the adjacent circuit but does not show it as usable since it is not electrically connected to the test system. Once the system is reconfigured, the CHMC detects the capacitor bank as usable. Additionally, the CHMC begins adjusting the VR set-point to compensate for the new system state.

E. Abnormal operation

To simulate an unscheduled topology change, the Light Load Day was simulated again, but this time a capacitor that is normally on at all times was taken out of service at 14:00.

Since the CHMC can detect the failed component, it can use the remaining control devices on the circuit to compensate for the lost capacitor. Table IV gives the losses, maximum feeder load, and feeder usage for each case. For the entire day, the CHMC is able to improve losses on the circuit over the normal case by 6.4% and reduce both the maximum feeder load and feeder usage by more than 7%.

IV. CONCLUSION

A configurable, hierarchical model-based control strategy has been presented. The CHMC control strategy automatically handles system reconfigurations that involve control devices being either added or removed from a circuit The strategy integrates legacy and modern control equipment to provide a topology independent, steady-state operating point for electrical distribution circuits. Another feature of the CHMC is that instead of controlling individual circuit measured variables, such as voltage or power factor, it works to control variable values summed for the entire circuit. The proposed CHMC is based around 3 properties of distribution systems:

1. A globally optimal circuit state is difficult to consistently attain in practice.
2. It is desirable to minimize the movement of control devices.
3. Some control actions are mutually exclusive.

In the simulations, a number of different circuit conditions were modeled and compared including a typical heavy load day, a typical light load day, and an abnormal light load day. The CHMC controller maintained voltage and capacity criteria throughout the circuit while significantly decreasing electrical losses. Over the cases considered, the proposed controller lowered losses from 4% to 7% when compared to the existing control strategy under the same conditions.

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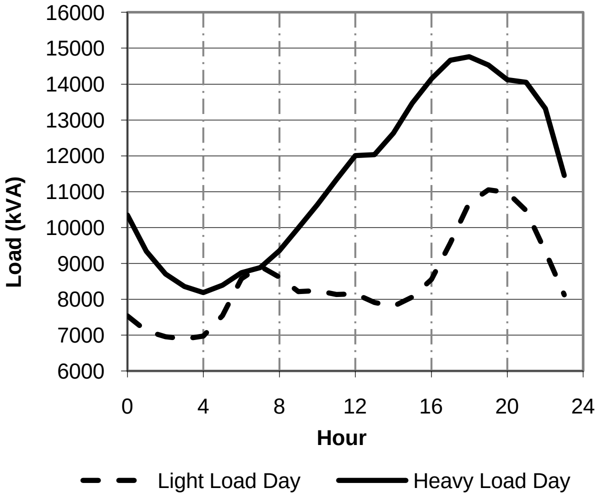

Fig. 5. Hourly load profiles for heavy and light load days

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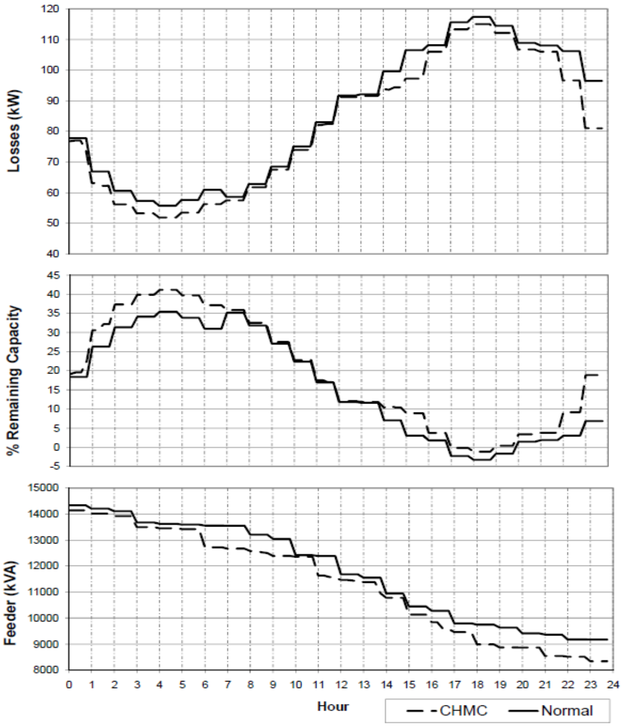

Fig. 6. Simulation results for heavy load day

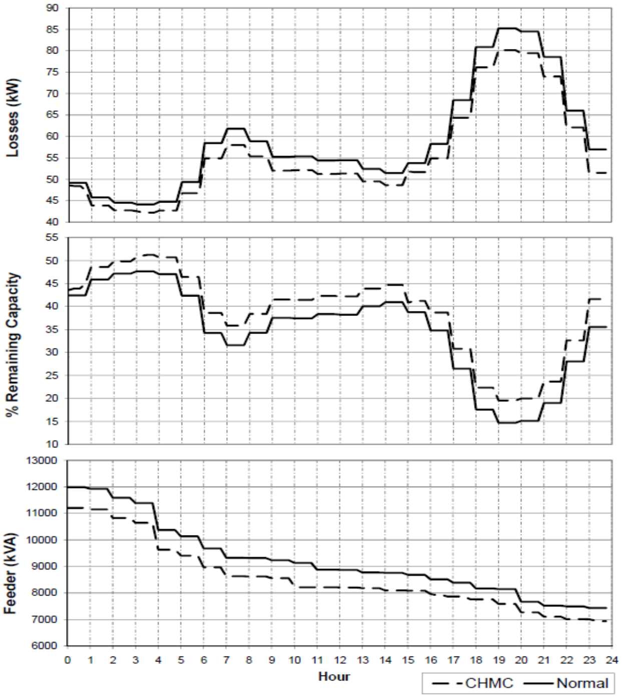

Fig. 7. Simulation results for light load day

TABLE IV

SIMULATION RESULTS FOR UNSCHEDULED CAPACITOR LOSS

	Normal Control	**CHMC**	**Improvement**
Losses	5,772 kw-hr	5,405 kw-hr	6.4 %
Maximum Feeder Load	12,351 kva	11,437 kva	7.4 %
Feeder Usage	224,616 kw-hr	207,158 kw-hr	7.8%

Change from Normal Case

	Normal Control	**CHMC**
Losses	122 kw-hr (2.2 %)	70 kw-hr (1.3%)
Maximum Feeder Load	364 kva (3.0%)	231 kva (2.1%)
Feeder Usage	3,230 kw-hr (1.5%)	1,101 kw-hr (.5%)

1