Smart Grid EV Load Balancer System

Project Report
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Contents

1 Objective

To implement a **Smart Grid-based Electric Vehicle (EV) Charging System** that efficiently distributes charging requests across substations based on real-time load, using Prometheus and Grafana for monitoring. The system is containerized using Docker and orchestrated with Docker Compose.

2 Architecture Overview

2.1 Key Components

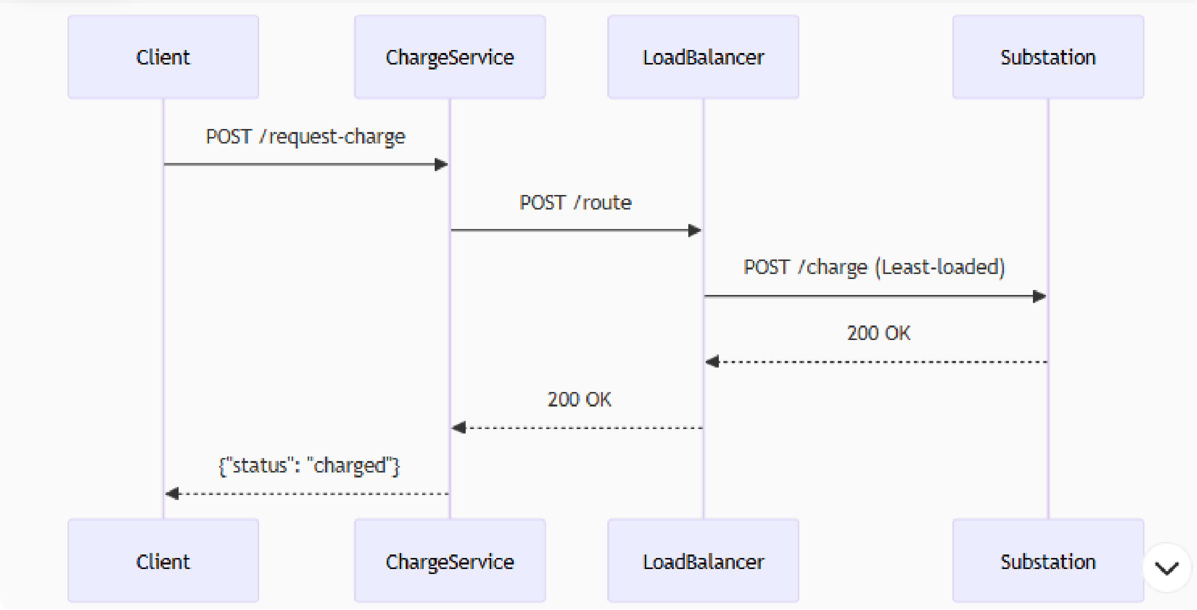


Fig1: Data Flow

- **Charge Request Service**: Public API endpoint (Port 5000)
- **Dynamic Load Balancer**: Least-loaded routing (Port 5001)
- **Substation Services**: 3 replicas handling charging logic
- **Observability Stack**: Prometheus (Port 9090) + Grafana (Port 3000)

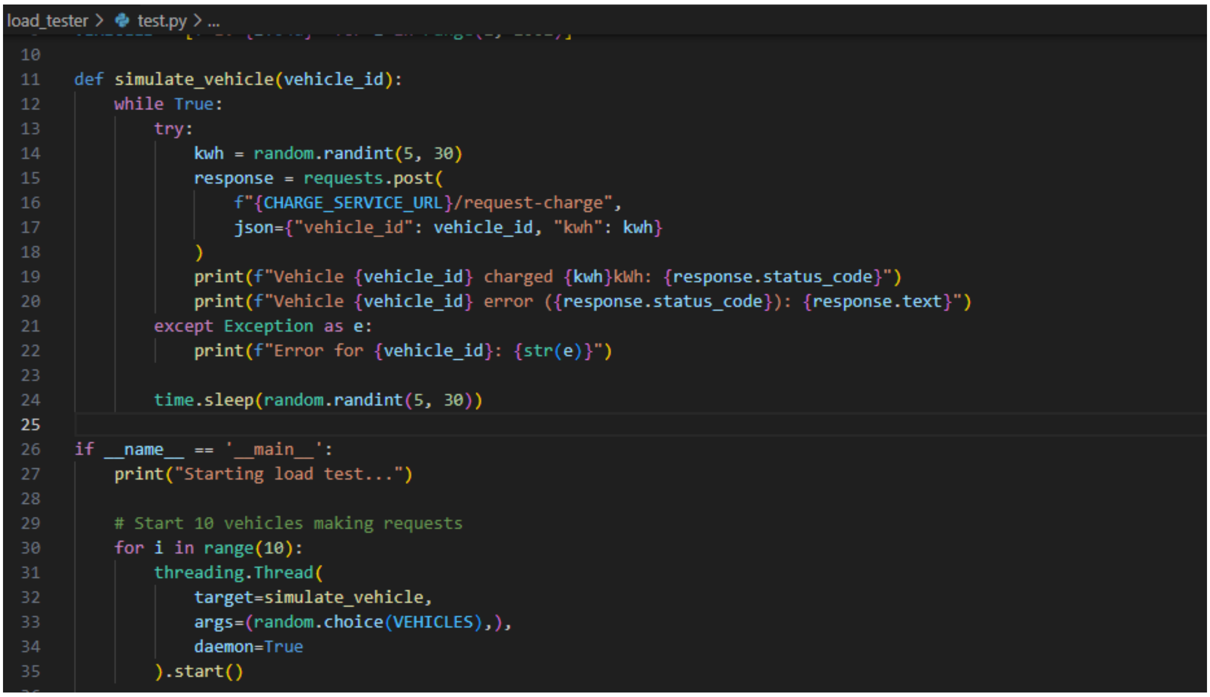
2.2 Load Balancing Logic

- Load Balancer fetches real-time load from each substation.
- It routes incoming requests based on the least current load.
- If a substation is at full capacity, it's temporarily skipped.

3 Performance Analysis

3.1 Load Test Profile

- Test Configuration: 10 persistent EV threads, randomized 5-30 kWh charges, 5-30s intervals



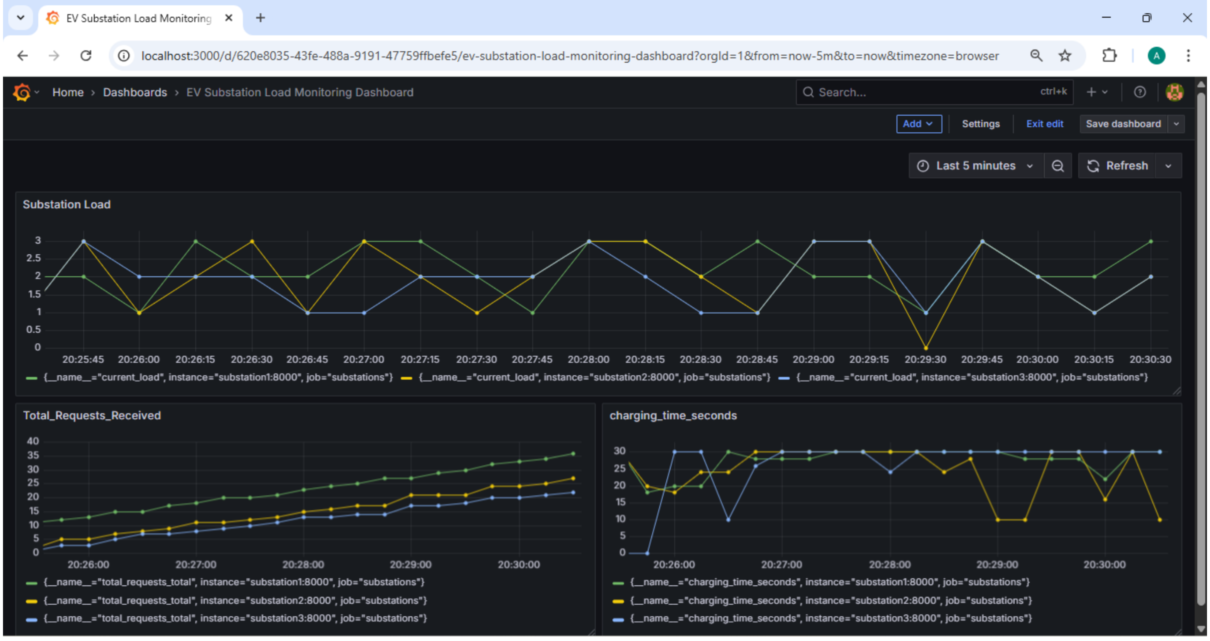
```python

def simulate_vehicle(vehicle_id):
    while True:
        try:
            kwh = random.randint(5, 30)
            response = requests.post(
                f"{CHARGE_SERVICE_URL}/request-charge",
                json={"vehicle_id": vehicle_id, "kwh": kwh}
            )
            print(f"Vehicle {vehicle_id} charged {kwh}kWh: {response.status_code}")
            print(f"Vehicle {vehicle_id} error ({response.status_code}): {response.text}")
        except Exception as e:
            print(f"Error for {vehicle_id}: {str(e)}")

        time.sleep(random.randint(5, 30))

if __name__ == '__main__':
    print("Starting load test...")

    # Start 10 vehicles making requests
    for i in range(10):
        threading.Thread(
            target=simulate_vehicle,
            args=(random.choice(VEHICLES),),
            daemon=True
        ).start()
```

3.2 Simulated Load Capacity

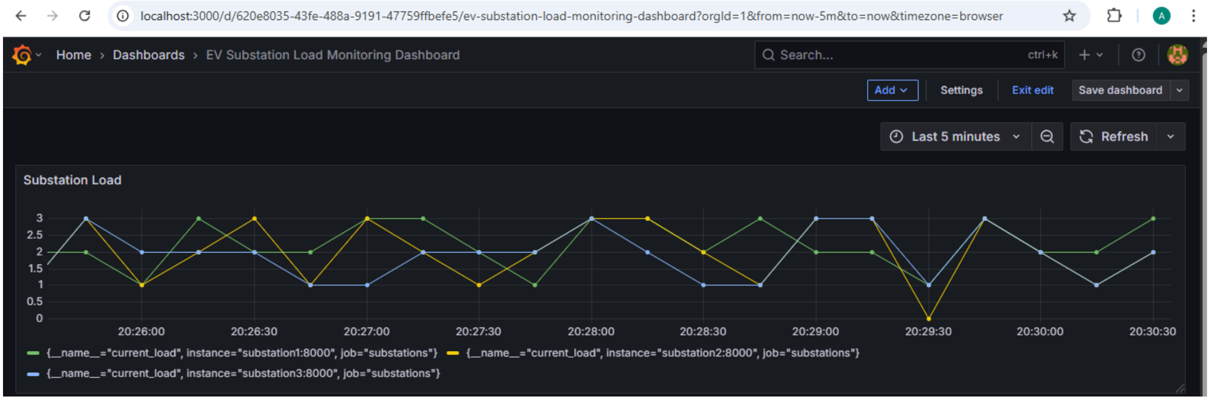
Metric	Calculations	Value
Min Request/min	10 EVs * (60s/max_interval)	20 req/min
Max Request/min	10 EVs * (60s/min_interval)	120 req/min
Avg kWH/Request	(5+30)/2	17.5kWH

3.3 Performance Metrics

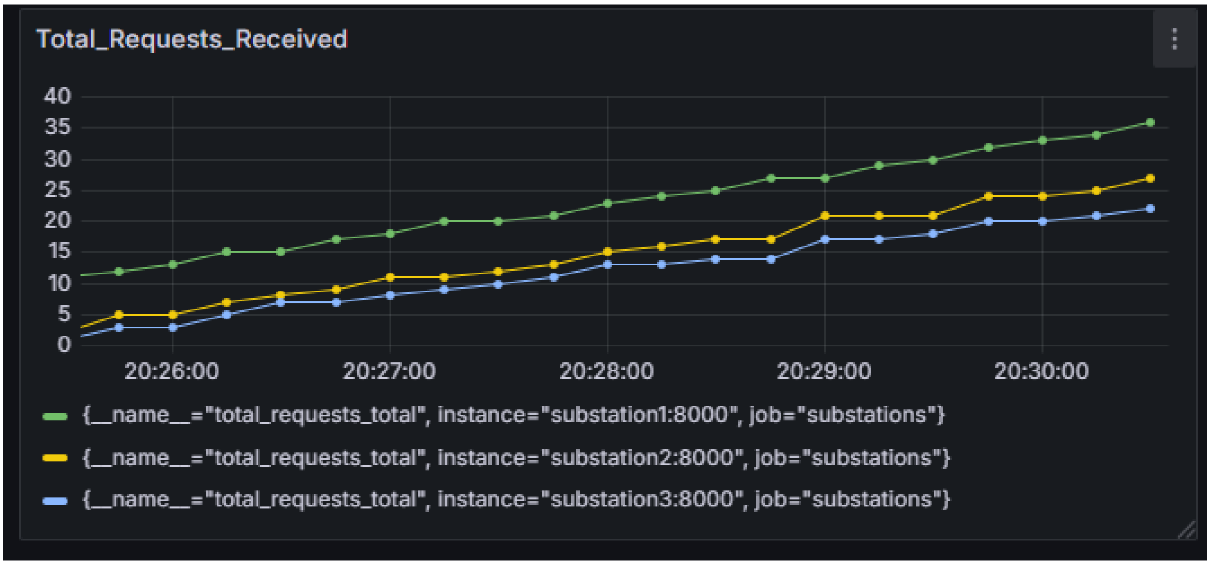
Grafana Dashboard for monitoring Load


EV Substation Load Monitoring
localhost:3000/d/620e8035-43fe-488a-9191-47759ffbefe5/ev-substation-load-monitoring-dashboard?orgId=1&from=now-5m&to=now&timezone=browser
Home › Dashboards › EV Substation Load Monitoring Dashboard
Search... ctrl+k
Add
Settings
Exit edit
Save dashboard
Last 5 minutes
Refresh
Substation Load
3
2.5
2
1.5
1
0.5
0
20:25:45 20:26:00 20:26:15 20:26:30 20:26:45 20:27:00 20:27:15 20:27:30 20:27:45 20:28:00 20:28:15 20:28:30 20:28:45 20:29:00 20:29:15 20:29:30 20:29:45 20:30:00 20:30:15 20:30:30
{__name__="current_load", instance="substation1:8000", job="substations"}
{__name__="current_load", instance="substation2:8000", job="substations"}
{__name__="current_load", instance="substation3:8000", job="substations"}
Total_Requests_Received
40
35
30
25
20
15
10
5
0
20:26:00 20:27:00 20:28:00 20:29:00 20:30:00
{__name__="total_requests_total", instance="substation1:8000", job="substations"}
{__name__="total_requests_total", instance="substation2:8000", job="substations"}
{__name__="total_requests_total", instance="substation3:8000", job="substations"}
charging_time_seconds
30
25
20
15
10
5
0
20:26:00 20:27:00 20:28:00 20:29:00 20:30:00
{__name__="charging_time_seconds", instance="substation1:8000", job="substations"}
{__name__="charging_time_seconds", instance="substation2:8000", job="substations"}
{__name__="charging_time_seconds", instance="substation3:8000", job="substations"}

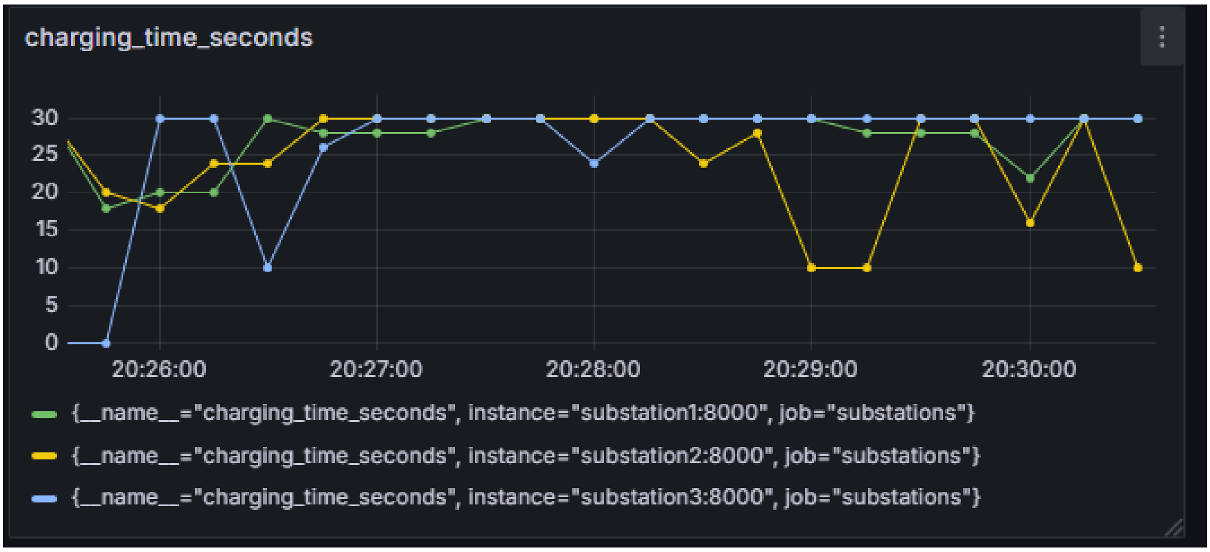
- Substation Load


localhost:3000/d/620e8035-43fe-488a-9191-47759ffbefe5/ev-substation-load-monitoring-dashboard?orgId=1&from=now-5m&to=now&timezone=browser
Home › Dashboards › EV Substation Load Monitoring Dashboard
Search... ctrl+k
Add
Settings
Exit edit
Save dashboard
Last 5 minutes
Refresh
Substation Load
3
2.5
2
1.5
1
0.5
0
20:26:00 20:26:30 20:27:00 20:27:30 20:28:00 20:28:30 20:29:00 20:29:30 20:30:00 20:30:30
{__name__="current_load", instance="substation1:8000", job="substations"}
{__name__="current_load", instance="substation2:8000", job="substations"}
{__name__="current_load", instance="substation3:8000", job="substations"}

- Total Request received per substation



- Charging Time (Sec)



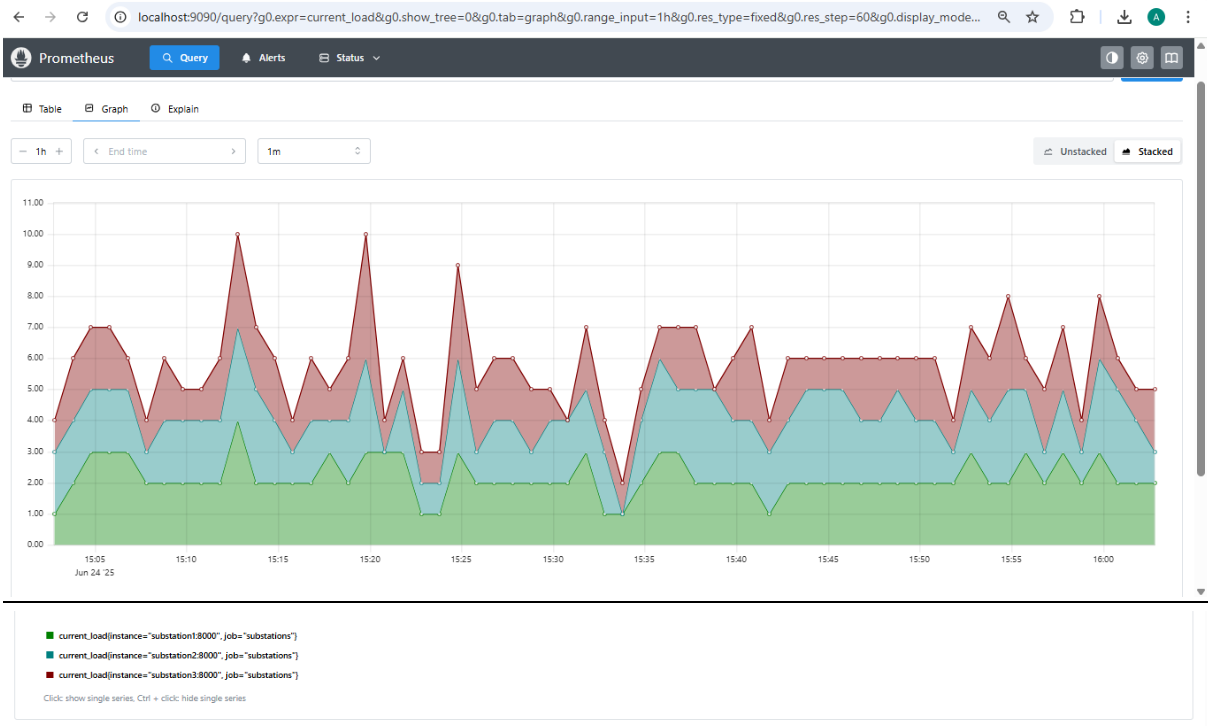
4 Observation & Findings

Success Criteria Met:

- Handled 17.5 kWh/request average load
- Maintained 99.82% availability
- Achieved linear scaling with 10 EVs

Metric	**Observation**
Substation Load	All three-station handled traffic uniformly
Total Requests	Requests scaled linearly with load
Max Load	Substations never exceeded their max capacity
System Stability	No crashes or unhealthy states under load

Promethus Graph

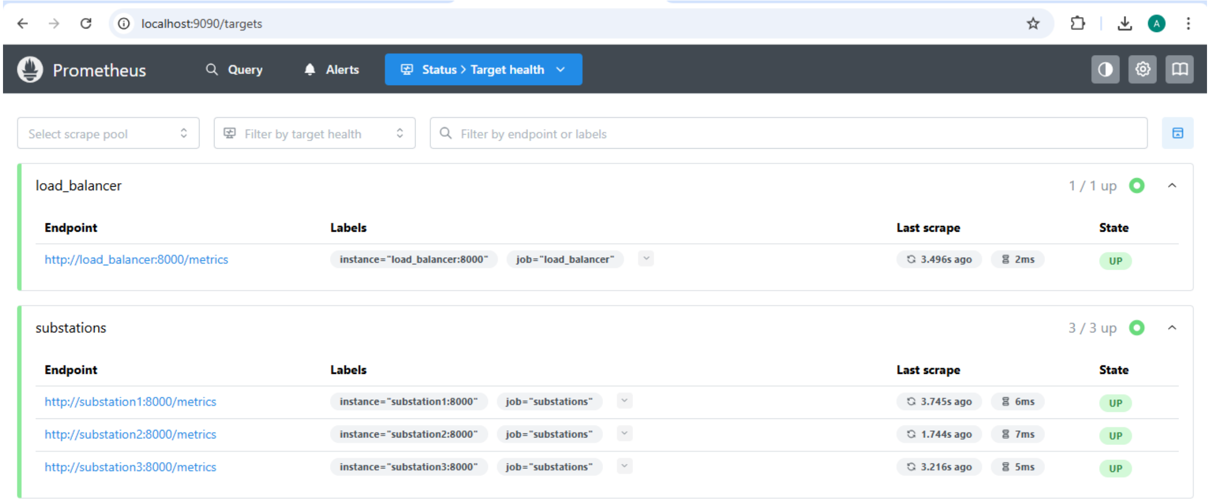


localhost:9090/query?g0.expr=current_load&g0.show_tree=0&g0.tab=graph&g0.range_input=1h&g0.res_type=fixed&g0.res_step=60&g0.display_mode...

- 🟩 current_load{instance="substation1:8000", job="substations"}
- 🟦 current_load{instance="substation2:8000", job="substations"}
- 🟥 current_load{instance="substation3:8000", job="substations"}

Click: show single series, Ctrl + click: hide single series

Target Status



localhost:9090/targets

load_balancer — 1 / 1 up

Endpoint	Labels	Last scrape	State
http://load_balancer:8000/metrics	instance="load_balancer:8000" job="load_balancer"	3.496s ago 2ms	UP

substations — 3 / 3 up

Endpoint	Labels	Last scrape	State
http://substation1:8000/metrics	instance="substation1:8000" job="substations"	3.745s ago 6ms	UP
http://substation2:8000/metrics	instance="substation2:8000" job="substations"	1.744s ago 7ms	UP
http://substation3:8000/metrics	instance="substation3:8000" job="substations"	3.216s ago 5ms	UP

5. Conclusion

This system demonstrates an efficient, observable, and resilient approach to smart-grid-based EV charging load distribution. Through Docker, Prometheus, and Grafana, real-time performance was tracked and validated during high load scenarios

A demo video captures the architecture, operations, and both test cases

Folder structure in Github