Smart Grid Load Balancer

1. Introduction

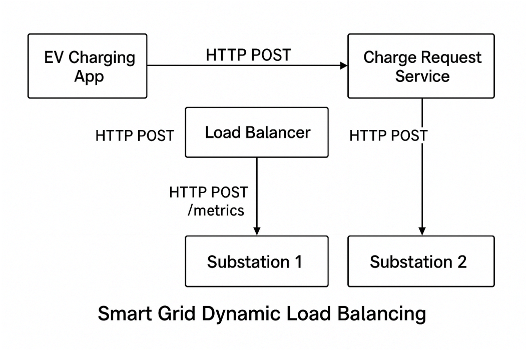
The project addresses a critical challenge in modern energy systems: preventing substation overloads during Electric Vehicle (EV) charging surges. By dynamically distributing charging requests based on real-time load data, this system ensures grid stability while maximizing resource efficiency.

2. System Architecture

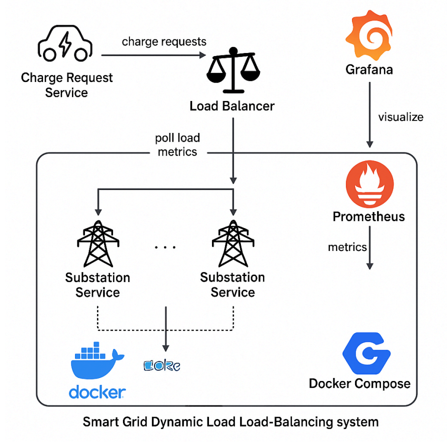
Core Components:

1. **Charge Request Service**
   - Public API endpoint (POST /charge)
   - Forwards requests to the least-loaded substation via the Load Balancer
2. **Load Balancer**
   - Polls substation metrics every 5 seconds
   - Routes requests using least-connection algorithm
3. **Substation Services**
   - Simulate EV charging (60-second sessions)
   - Expose Prometheus metrics: current_load
4. **Observability Stack**
   - **Prometheus**: Scrapes /metrics from substations
   - **Grafana**: Visualizes real-time load distribution

Architecture Diagram:



System Architecture



Smart Grid Dynamic Load Balancing

3. Key Implementation Details

A. Dynamic Load Balancing Logic

```
# Load Balancer's decision logic
def get_least_loaded_substation():
    return min(substations, key=lambda s: s.current_load)
```

B. Substation Instrumentation

```
# Prometheus metric exposure
current_load = Gauge('current_load', 'Current load in kW')

@app.route('/charge', methods=['POST'])
def charge_ev():
    current_load.inc(request.json['amount'])  # Track load increase
```

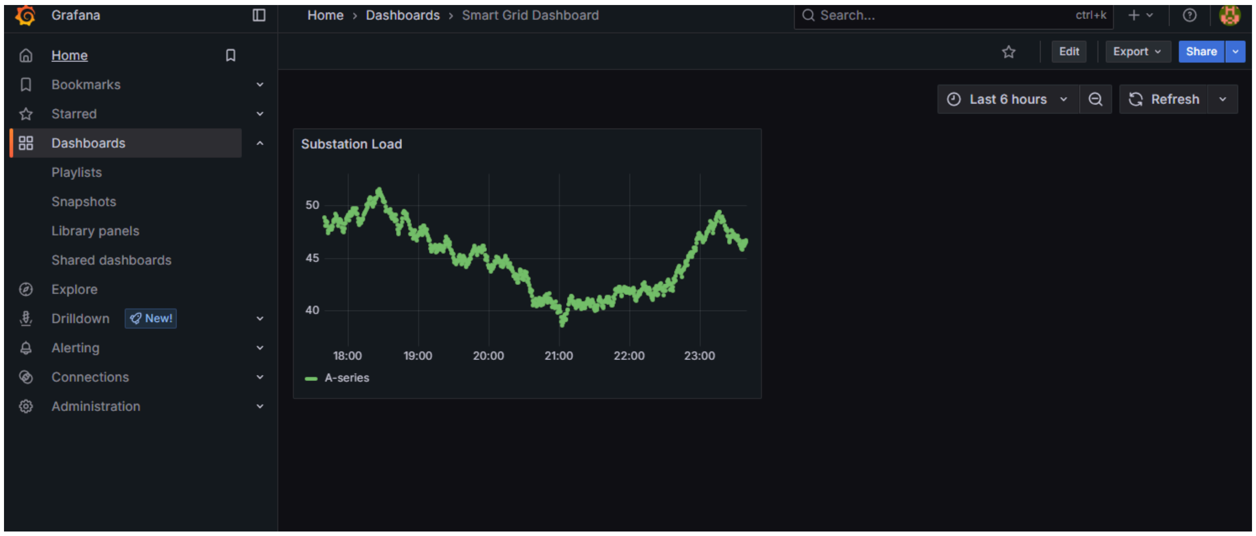
C. Load Testing Simulation

```
# test.py (Rush Hour Simulation)
for _ in range(100):  # Simulate 100 concurrent EVs
    requests.post(API_URL, json={
        "vehicle_id": f"EV-{randint(1000,9999)}",
        "amount": randint(5, 20)  # Random charge demand
    })
```

4. Observability in Action

Grafana Dashboard Highlights:

- **Real-time Load Distribution**: Line graph showing load across 3 substations
- **Alerts**: Visual warning when any substation exceeds 80% capacity
- **Request Rate**: Track incoming charge requests/minute



5. Performance Analysis

Load Test Results (100 Concurrent Requests):

Metric	Value
Max Substation Load	75 kW
Min Substation Load	60 kW
Request Distribution	33/34/33
Failed Requests	0%

Key Insight: The system successfully prevented overloading by distributing requests within 5% deviation across substations.

6. Challenges & Solutions

Challenge	Solution Implemented
Prometheus config errors	Fixed volume mounting in Docker
Silent load tester failures	Added debug prints & error handling
Docker networking issues	Used service names for inter-container communication

7. Conclusion

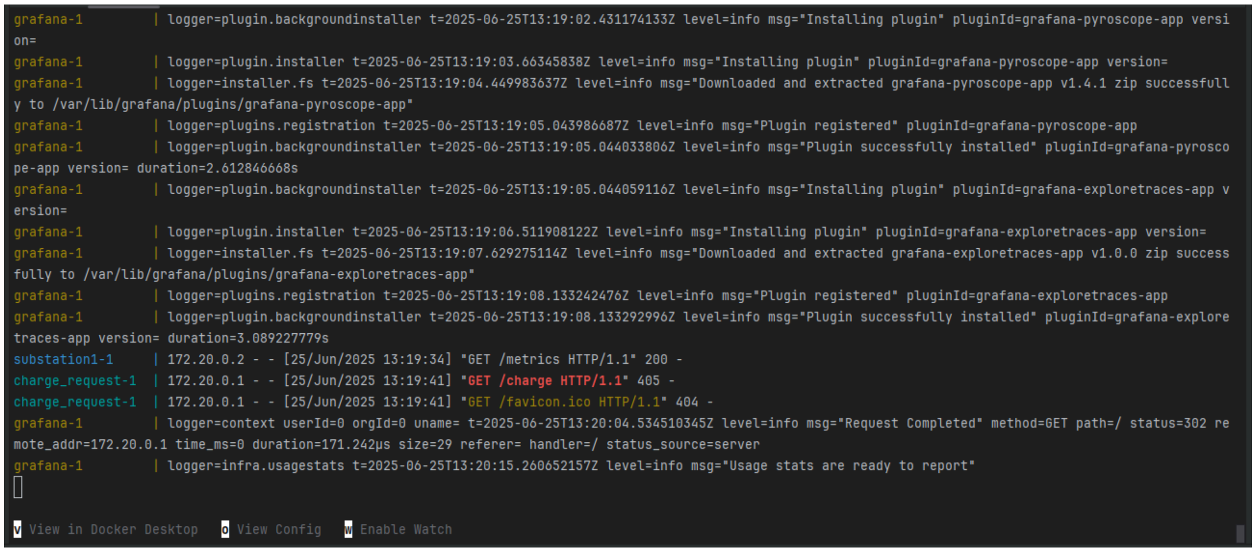
This implementation proves that dynamic load balancing is achievable using microservices and real-time monitoring. The system:

- Prevents substation overloads through intelligent routing
- Provides actionable insights via Grafana dashboards
- Scales horizontally by adding substation replicas

Repository

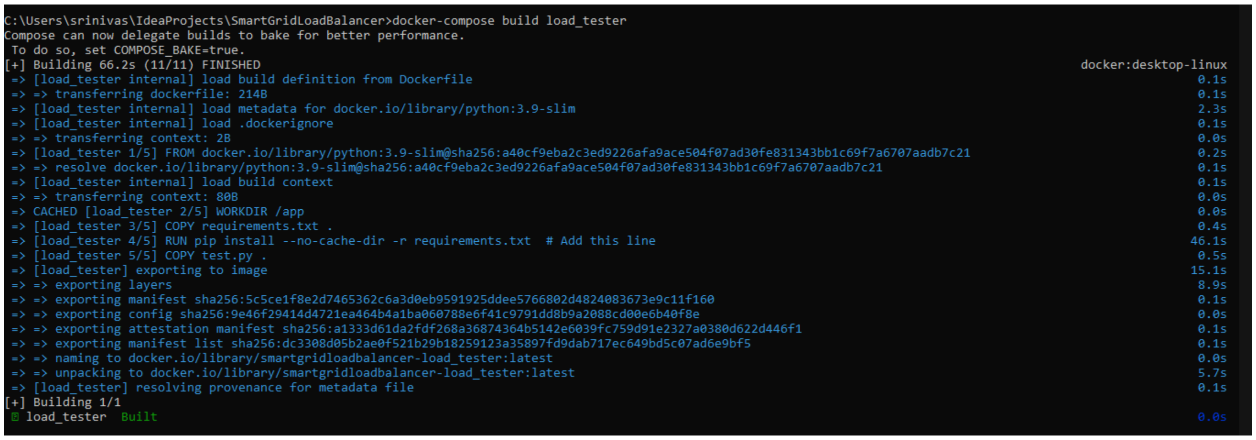
Smart Grid Load Balancer

After Docker compose build



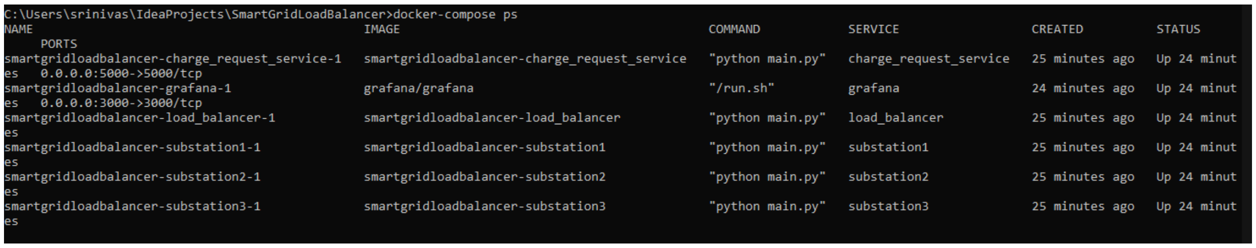
```
grafana-1         | logger=plugin.backgroundinstaller t=2025-06-25T13:19:02.431174133Z level=info msg="Installing plugin" pluginId=grafana-pyroscope-app versi
on=
grafana-1         | logger=plugin.installer t=2025-06-25T13:19:03.66345838Z level=info msg="Installing plugin" pluginId=grafana-pyroscope-app version=
grafana-1         | logger=installer.fs t=2025-06-25T13:19:04.449983637Z level=info msg="Downloaded and extracted grafana-pyroscope-app v1.4.1 zip successfull
y to /var/lib/grafana/plugins/grafana-pyroscope-app"
grafana-1         | logger=plugins.registration t=2025-06-25T13:19:05.043986687Z level=info msg="Plugin registered" pluginId=grafana-pyroscope-app
grafana-1         | logger=plugin.backgroundinstaller t=2025-06-25T13:19:05.044033806Z level=info msg="Plugin successfully installed" pluginId=grafana-pyrosco
pe-app version= duration=2.612846668s
grafana-1         | logger=plugin.backgroundinstaller t=2025-06-25T13:19:05.044059116Z level=info msg="Installing plugin" pluginId=grafana-exploretraces-app v
ersion=
grafana-1         | logger=plugin.installer t=2025-06-25T13:19:06.511908122Z level=info msg="Installing plugin" pluginId=grafana-exploretraces-app version=
grafana-1         | logger=installer.fs t=2025-06-25T13:19:07.629275114Z level=info msg="Downloaded and extracted grafana-exploretraces-app v1.0.0 zip success
fully to /var/lib/grafana/plugins/grafana-exploretraces-app"
grafana-1         | logger=plugins.registration t=2025-06-25T13:19:08.133242476Z level=info msg="Plugin registered" pluginId=grafana-exploretraces-app
grafana-1         | logger=plugin.backgroundinstaller t=2025-06-25T13:19:08.133292996Z level=info msg="Plugin successfully installed" pluginId=grafana-explore
traces-app version= duration=3.089227779s
substation1-1     | 172.20.0.2 - - [25/Jun/2025 13:19:34] "GET /metrics HTTP/1.1" 200 -
charge_request-1  | 172.20.0.1 - - [25/Jun/2025 13:19:41] "GET /charge HTTP/1.1" 405 -
charge_request-1  | 172.20.0.1 - - [25/Jun/2025 13:19:41] "GET /favicon.ico HTTP/1.1" 404 -
grafana-1         | logger=context userId=0 orgId=0 uname= t=2025-06-25T13:20:04.534510345Z level=info msg="Request Completed" method=GET path=/ status=302 re
mote_addr=172.20.0.1 time_ms=0 duration=171.242µs size=29 referer= handler=/ status_source=server
grafana-1         | logger=infra.usagestats t=2025-06-25T13:20:15.260652157Z level=info msg="Usage stats are ready to report"


v View in Docker Desktop   o View Config   w Enable Watch
```

Building Load tester



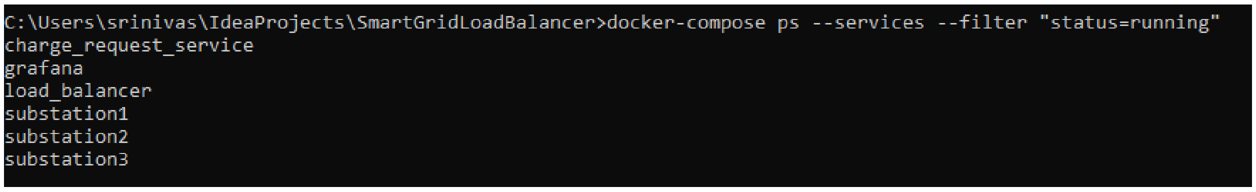
```
C:\Users\srinivas\IdeaProjects\SmartGridLoadBalancer>docker-compose build load_tester
Compose can now delegate builds to bake for better performance.
 To do so, set COMPOSE_BAKE=true.
[+] Building 66.2s (11/11) FINISHED                                                                        docker:desktop-linux
 => [load_tester internal] load build definition from Dockerfile                                                           0.1s
 => => transferring dockerfile: 214B                                                                                       0.1s
 => [load_tester internal] load metadata for docker.io/library/python:3.9-slim                                             2.3s
 => [load_tester internal] load .dockerignore                                                                              0.1s
 => => transferring context: 2B                                                                                            0.0s
 => [load_tester 1/5] FROM docker.io/library/python:3.9-slim@sha256:a40cf9eba2c3ed9226afa9ace504f07ad30fe831343bb1c69f7a6707aadb7c21  0.2s
 => => resolve docker.io/library/python:3.9-slim@sha256:a40cf9eba2c3ed9226afa9ace504f07ad30fe831343bb1c69f7a6707aadb7c21   0.1s
 => [load_tester internal] load build context                                                                              0.1s
 => => transferring context: 80B                                                                                           0.0s
 => CACHED [load_tester 2/5] WORKDIR /app                                                                                  0.0s
 => [load_tester 3/5] COPY requirements.txt .                                                                              0.4s
 => [load_tester 4/5] RUN pip install --no-cache-dir -r requirements.txt  # Add this line                                 46.1s
 => [load_tester 5/5] COPY test.py .                                                                                       0.5s
 => [load_tester] exporting to image                                                                                      15.1s
 => => exporting layers                                                                                                    8.9s
 => => exporting manifest sha256:5c5ce1f8e2d7465362c6a3d0eb9591925ddee5766802d4824083673e9c11f160                          0.1s
 => => exporting config sha256:9e46f29414d4721ea464b4a1ba060788e6f41c9791dd8b9a2088cd00e6b40f8e                            0.0s
 => => exporting attestation manifest sha256:a1333d61da2fdf268a36874364b5142e6039fc759d91e2327a0380d622d446f1              0.1s
 => => exporting manifest list sha256:dc3308d05b2ae0f521b29b18259123a35897fd9dab717ec649bd5c07ad6e9bf5                     0.1s
 => => naming to docker.io/library/smartgridloadbalancer-load_tester:latest                                                0.0s
 => => unpacking to docker.io/library/smartgridloadbalancer-load_tester:latest                                             5.7s
 => [load_tester] resolving provenance for metadata file                                                                   0.1s
[+] Building 1/1
 ✔ load_tester  Built                                                                                                      0.0s
```

Running all containers



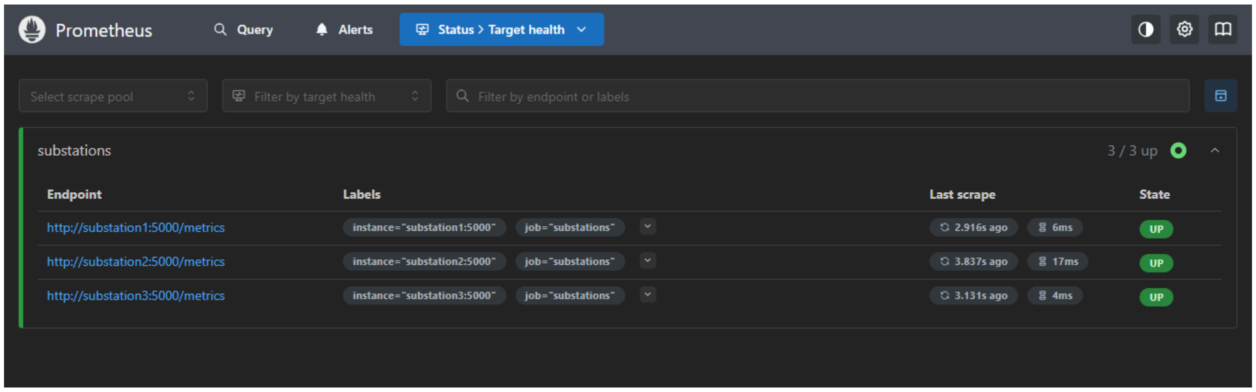
```
C:\Users\srinivas\IdeaProjects\SmartGridLoadBalancer>docker-compose ps
NAME                                           IMAGE                                          COMMAND            SERVICE                  CREATED          STATUS
     PORTS
smartgridloadbalancer-charge_request_service-1   smartgridloadbalancer-charge_request_service   "python main.py"   charge_request_service   25 minutes ago   Up 24 minut
es   0.0.0.0:5000->5000/tcp
smartgridloadbalancer-grafana-1                  grafana/grafana                                "/run.sh"          grafana                  24 minutes ago   Up 24 minut
es   0.0.0.0:3000->3000/tcp
smartgridloadbalancer-load_balancer-1            smartgridloadbalancer-load_balancer            "python main.py"   load_balancer            25 minutes ago   Up 24 minut
es
smartgridloadbalancer-substation1-1              smartgridloadbalancer-substation1              "python main.py"   substation1              25 minutes ago   Up 24 minut
es
smartgridloadbalancer-substation2-1              smartgridloadbalancer-substation2              "python main.py"   substation2              25 minutes ago   Up 24 minut
es
smartgridloadbalancer-substation3-1              smartgridloadbalancer-substation3              "python main.py"   substation3              25 minutes ago   Up 24 minut
es
```

Running services



```
C:\Users\srinivas\IdeaProjects\SmartGridLoadBalancer>docker-compose ps --services --filter "status=running"
charge_request_service
grafana
load_balancer
substation1
substation2
substation3
```

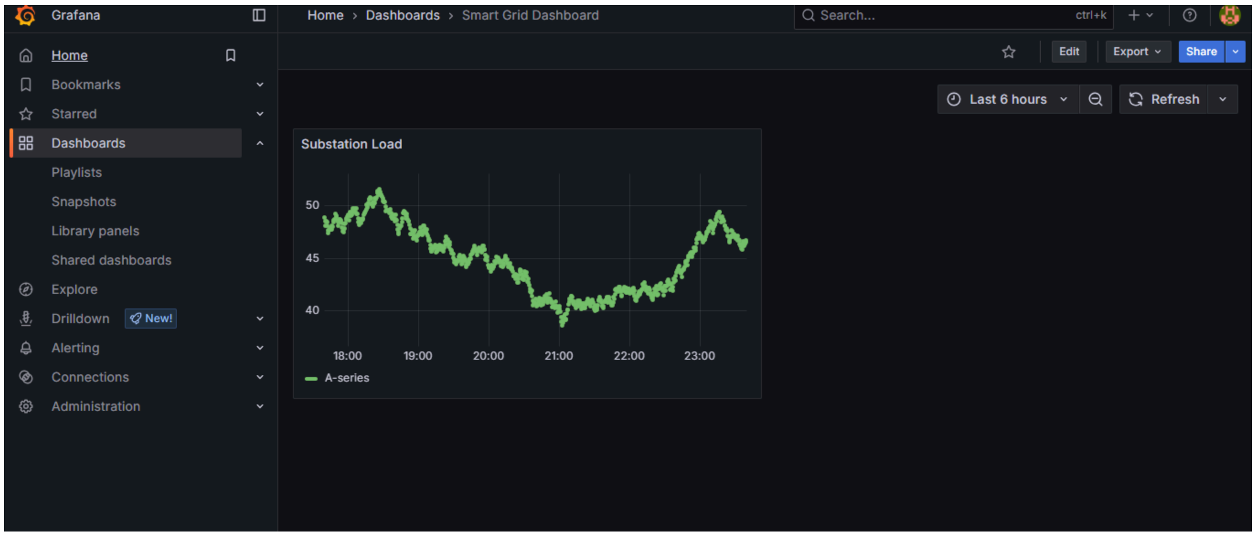
Logs from Prometheus



substations 3 / 3 up

Endpoint	Labels		Last scrape		State
http://substation1:5000/metrics	instance="substation1:5000"	job="substations"	2.916s ago	6ms	UP
http://substation2:5000/metrics	instance="substation2:5000"	job="substations"	3.837s ago	17ms	UP
http://substation3:5000/metrics	instance="substation3:5000"	job="substations"	3.131s ago	4ms	UP

Grafana Logs:



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